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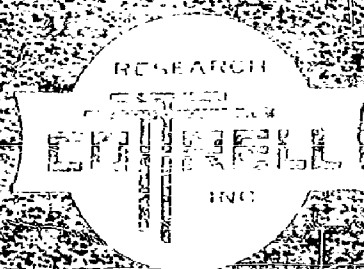
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MOVEMENT OF AIR IN THE
ELECTRIC WIND OF THE
CORONA DISCHARGE

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TECHNICAL PAPER TP60-2

MOVEMENT OF AIR IN THE ELECTRIC WIND
OF THE CORONA DISCHARGE

Nobs 77164

Index No. NS-600-010

June 8, 1960

M. Robinson

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ABSTRACT

The mechanism of gas movement in the electric wind is considered and an approximate theory presented which relates relevant electrical and mechanical quantities. Among others, the following relationships are shown to hold: Velocity is a linear function of voltage and is proportional to the square root of current; if the density of the gas is not too low the efficiency of electrokinetic conversion is proportional to the density and the velocity is independent of the density; near sparkover efficiency is independent of voltage; velocity increases slowly as blowers are stacked in series; the rate of ozone generation in the corona discharge in air is an increasing function of electric-wind velocity. The forms of the equations relating these variables are found to hold in a variety of cases even though assumed boundary conditions are not observed experimentally. The practical utility of an electrostatic blower is limited by an efficiency of operation in the neighborhood of one percent. A survey of the literature and an extensive bibliography are included.

INTRODUCTION

The phenomenon variously known as the electric wind, corona wind and electric aura refers to the movement of gas induced by the repulsion of ions from the neighborhood of a high-voltage discharge electrode. The effect is most commonly observed with atmospheric air, but other gases and insulating liquids may also be employed as the ion source and carrier medium.

In the following study we shall be concerned chiefly with air and shall examine the practicability of using the electric wind as an air-moving mechanism. An electrostatic* blower operating on this principle directly converts electrical energy into the kinetic energy of a moving gas stream. Thus, lacking moving parts, it can have advantages over conventional fans in areas of application where high-voltage low-current power is available, simple sturdy construction is required and noise, gyroscopic effects and other consequences of rotational motion cannot be tolerated. On the other hand, for gases but not necessarily for liquids, the electrostatic blower is seriously handicapped by an efficiency of electrokinetic conversion of about one percent as compared to 60 or 70 percent commonly found in conventional fans.

The older textbooks on electricity and magnetism almost invariably contained a discussion of the electric wind. Today, this phenomenon, which was deemed worthy of attention by Newton, Faraday, Maxwell, and a host of others, is generally ignored. The current literature on the subject is scanty and an up-to-date bibliography apparently does not exist. The only comprehensive surveys of the literature seem to be that of Tomlinson (99), in English, covering the period 1760-1864, and that of Lehman, in German, for the period 1760-1898 (61, 62). It is of practical importance and historical interest to extend these dates in both directions. The appended review and bibliography will, therefore, be longer than is customary in a report of this type.

*In conformity with frequent usage electrostatics is taken to include low-current, high-voltage processes. An electrostatic blower may draw hundreds of microamperes of current and is, therefore not strictly a static device.

THEORY

Electrical fundamentals. If an electric field is impressed upon an ionized gas the ions will traverse the field and, by repeated collision with the uncharged molecules present, induce an overall motion in the surrounding volume of gas. The corona discharge in air offers the simplest means for establishing these conditions. For a noticeable electric-wind effect, it is not necessary that the gas be heavily ionized. Indeed, heavy ionization is not possible in the corona discharge. For atmospheric air, under the experimental conditions to be described, a maximum concentration of one ion per 10^{10} molecules is characteristic.

An electrostatic blower consists essentially of an arrangement of emitting and collecting electrodes permeable to the gas being moved. Each infinitesimal volume of gas between the electrodes contains an electric charge of density ρ coul/m³* and is acted upon by an electric field of intensity \vec{E} newton/coul (mv/m)**. The product $\rho\vec{E}$ therefore gives the electrical force exerted on a unit volume of charged gas. Force per unit volume is the force per unit area per unit distance perpendicular to the area in question and may be represented as a pressure gradient

$$\vec{\nabla}p = \rho\vec{E}, \quad (1)$$

where p is the pressure in newton/m². Field intensity and space-charge density are related by Poisson's equation

$$\vec{\nabla} \cdot \vec{E} = \rho/\epsilon \quad (2)$$

where ϵ is the absolute dielectric constant of the gas in farad/m. Equation (2) enables us to eliminate ρ from Equation (1)

$$\vec{\nabla}p = \epsilon\vec{E}(\vec{\nabla} \cdot \vec{E}). \quad (3)$$

The impressed voltage V (v) is equal to the difference in potential across the two electrodes. The potential ϕ (v) anywhere in the system is given by

$$\vec{E} = -\vec{\nabla}\phi. \quad (4)$$

The passage of current between the electrodes is the result of two simultaneous effects: (1) movement of charge relative to the main body of gas and (2) transport of charge by, rather than through, the gas stream. Assuming that the space charge consists wholly of ions of one kind, a condition that is closely

* The m.k.s. system of units is used throughout.

** A bar over a symbol designates a vector. A newton is approximately 0.22 lb force.

satisfied outside the active region of corona glow, the first component of velocity is $b\bar{E}$, where b is the ionic mobility in (m/sec)/(v/m). If \bar{v} is the gas velocity (m/sec) relative to the electrode system, i.e. the velocity of the electric wind, the total ionic velocity \bar{v}_t is

$$\bar{v}_t = \bar{v} + b\bar{E}. \quad (5)$$

The current density j (amp/m²) in the region between the electrodes is then given by

$$\bar{j} = \rho \bar{v}_t = \rho(\bar{v} + b\bar{E}). \quad (6)$$

Eliminating ρ between Equations (2) and (6) we have

$$\bar{j} = \epsilon(\bar{v} \cdot \bar{E})(\bar{v} + b\bar{E}). \quad (7)$$

From Equations (3) and (4) we can express the generated pressure as a function of the applied voltage. Equations (7) and (4) give the current in terms of the voltage. We require only a relationship linking pressure and velocity and the performance of the electrostatic blower will be completely described.

It is interesting to note that if $\bar{v} \ll b\bar{E}$ we have $\bar{j} = b\rho\bar{E}$, i.e. force per unit volume $\rho\bar{E}$ is proportional to current density.

Electrokinetic considerations. Air will move through a blower at the velocity at which the aerodynamic back pressure is equal to the forward electrical pressure. The total back pressure is the sum of the individual pressure drops across each of the elements of the blower system. The following pressure losses are encountered (77, 86):

1. Entry loss = $K_1 \rho_g v^2 / 2$. ρ_g is the gas density (kg/m³). K_1 varies from ≈ 0.04 for a properly curved entrance to ≈ 0.9 for a plain open end (re-entrant) pipe.

2. Loss along straight duct = $f L \rho_g v^2 / 2D$. L is the pipe length and D the diameter. The Reynolds number R_g is equal to $L v \rho_g / \mu$ where μ is the viscosity of the gas (dekapoise). For $R_g > 2,000$, i.e. turbulent flow, the condition existing in the experimental blowers, the friction factor f for smooth pipe is given closely by $0.316/R_g^{1/4}$.

3. Losses at expansions and contractions = $K_2 \rho_g v^2 / 2$. The loss coefficient K_2 is a function of geometry.

4. Loss at change in direction = $K_3 \rho_g v^2 / 2$. K_3 is a function of geometry.

5. Discharge loss = $K_4 \rho_g v^2 / 2$. $K_4 = 2.0$ for re-entrant pipe.

6. Screen loss = $K_5 \rho_g v^2 / 2$. This is applicable when the collecting electrode is a screen (+). If d is the diameter of

screen wire and s the wire separation, the porosity is given by $\beta = (1-s/d)^2$. At normal incidence and $\beta = 0.6$, K_5 is essentially independent of v except at very low velocities. Empirically $K_5 = 0.47 (\beta^2 - 0.57)$. The foregoing relations vary somewhat with type of turbulence.

Except for the straight duct and screen losses, each of the above pressure drops is proportional to the square of the velocity. If the screen is suitably chosen, the screen loss will be so proportional also. For a blower the length of which is not much larger than its diameter the straight duct loss is negligible. In a longer blower the loss coefficient may, to a first approximation, be considered constant. (Over the range of velocity of 0.8 to 8 m/sec f varies from 4.4×10^{-2} to 2.4×10^{-2} for a 7-cm diameter blower duct in room air.) We may thus write

$$p = (K_1 + K_2 + fL/D + K_3 + K_4 + K_5)(\rho_g v^2/2) - K\rho_g v^2/2. \quad (8)$$

Equations (1) and (6) yield another useful relationship

$$\bar{\nabla} p = (\bar{j} - \rho \bar{v})/b. \quad (9)$$

The quantity $\rho \bar{v}$ is the extent to which the current density is increased by the carrier fluid moving under the influence of migrating ions. In liquids $\rho \bar{v}$ may be comparable to \bar{j} ; in gases it is, for our purpose, negligible. We have, then,

$$\bar{\nabla} p \approx \bar{j}/b. \quad (10)$$

We shall confine our attention to plane parallel, concentric spherical and coaxial cylindrical electrode configurations. A plane electrode supporting a corona discharge is, of course, not realizable in practice. A plane parallel system is, nevertheless, an adequate approximation to certain practical geometries. Concentric spherical electrodes, in their simplest experimental form comprise a point discharge and a segment of a spherical surface, the latter serving as the collecting electrode. Coaxial cylinders are conveniently represented by a discharging wire and a segment of a coaxial cylindrical surface.

It is assumed that the electrical and aerodynamic boundary conditions are identical. Hence the directions of the vectors \bar{i} , \bar{j} and \bar{v} are taken to be the same at any given point in the inter-electrode region. In order to conform to this restriction, only the plane parallel blower can be built in a duct of uniform cross section. The spherical electrodes must be housed in a conical duct and the cylindrical electrodes in a wedge-shaped duct. It will be shown, however, that marked departures from these conditions need not invalidate the functional forms of the relationships between the variables.

In each of the three coordinate systems mentioned the pressure gradient is given by

$$\left| \vec{\nabla} p \right| = dp/dr \quad (11)$$

where r is the distance from the discharge electrode. Thus, for gases, the pressure differential maintaining the electric wind is

$$p = \int_{r_d}^{r_c} \frac{1}{b} dr \quad (12)$$

where r_d and r_c are, respectively, the coordinates of the discharge and collecting electrodes.

Assuming constant mobility, Equations (8) and (12) combine to give

$$v_c = \left[\frac{2}{K \rho_g b} \int_{r_d}^{r_c} j dr \right]^{1/2} \quad (13)$$

where $j = j(r, r_c, r_d)$. In an expanding flue the loss coefficient K is an increasing function of r_c . The quantity v_c designates the velocity of the gas as it passes through the collecting electrode. The current density is dependent on the geometry of the system and is, in addition, proportional to the current. Consequently,

$$v_c = g_1 (i / \rho_g b K)^{1/2} \quad (14)$$

where g_1 is an appropriate function of the geometry ($m^{-1/2}$) and i is the current (amp). The gas velocity is thus proportional to the square root of the current.

Since in gases, the electric-wind velocity is very much less than the ionic velocity relative to the gas, Equation (7) simplifies to

$$\vec{j} = b \vec{E} \vec{\nabla} \cdot \vec{E} \quad (15)$$

From the solution to this equation the current may be expressed as a function of the voltage. By assuming an appropriate form for the electric-field strength at the discharge electrode, this current-voltage relationship has been shown, for certain geometries (93, 21, 66), to be

$$i = g_2 \epsilon b V (V - V_0) \quad (16)$$

where g_2 (m^{-1}) is a function of the geometry, ϵ is the dielectric constant of the gas (farad/m), and V_0 is the apparent corona-starting voltage. Equation (16) finds experimental confirmation over a much wider range of geometries than for which analytical solutions of Equation (15) are available, and may be assumed generally true for space-charge limited discharges of the kind considered (67).

Substituting Equation (16) in Equation (14) and setting $g_1 g_2^{1/2} = g_3$ (m^{-1}) there results

$$v_c = g_3 (\epsilon / \rho_g K)^{1/2} [V(V - V_0)]^{1/2}. \quad (17)$$

We are mainly interested in the region $V \gg V_0$. Expanding the bracketed term, we obtain

$$v_c = g_3 (\epsilon / \rho_g K)^{1/2} (V - V_0/2 + \dots) \quad (18)$$

an approximate linear relationship between velocity and voltage.

The kinetic energy of a mass of air M (kg) emerging from a blower in a time interval t (sec) is $Mv^2/2$. The kinetic power output P_o (w) is then given by

$$P_o = \frac{d}{dt} \left(\frac{1}{2} M v_c^2 \right) = \frac{1}{2} \frac{dM}{dt} v_c^2 = \frac{1}{2} \rho_g A v_c^3 \quad (19)$$

where A (m^2) is the cross-sectional area of the duct at $r=r_c$. Alternatively, we may write, using Equations (17) and (19)

$$P_o = (g_3^3 / \rho_g K^3)^{1/2} [V(V - V_0)]^{3/2} \quad (20)$$

where $g_4 = g_3^3 A$ (m^{-1}).

The fractional efficiency of electrokinetic conversion η is defined as

$$\eta = P_o / P_i \quad (21)$$

where $P_i = VI$ is the electrical power input (w). Setting

$$Z_1 = g_1^3 g_2^{1/2} A / \rho_g \quad (\text{dimensionless}) \quad (22)$$

we have

$$\eta = (g_4/b)(\epsilon/\rho_g K^3)^{1/2} [(V-V_s)/V]^{1/2}. \quad (23)$$

The electrical power input may be divided into two parts, V_{pi} , the power necessary for ion generation in the corona discharge, and $(V-V_s)i$, the power consumed in maintaining an ionic current across the electrode gap (90). In order that the calculated efficiency may be compared with that of a blower provided with an ion source other than a corona discharge, it is convenient to take the quantity $(V-V_s)i$ as the power input. Accordingly,

$$\eta' = P_o/(V-V_s)i = (g_4/b)(\epsilon/\rho_g K^3)^{1/2} [V/(V-V_s)]^{1/2}. \quad (24)$$

In order to achieve maximum output, it is necessary to operate a blower close to sparkover. The efficiency normally attained in practice is, therefore,

$$\eta \approx \eta' \approx \eta_o = (g_4/b)(\epsilon/\rho_g K^3)^{1/2}. \quad (25)$$

The quantities b , ϵ , and ρ_g are known. The loss coefficient K may be estimated (77,86) once the geometry is selected, but for greatest accuracy is best determined experimentally. The functions g may be calculated subject to certain simplifying, and perhaps invalidating, assumptions. They should, in all cases, be checked experimentally.

Calculation of g 's. The g 's are found as follows. Let the subscripts p , y , and s designate plane parallel, cylindrical and spherical electrode systems respectively. We have then

$$g_p = 1/A \quad (26)$$

$$g_y = 1/r_c \theta l \quad (27)$$

$$g_s = 1/r_c^2 \Omega \quad (28)$$

where θ is the plane angle subtended by the segment of the cylindrical surface forming the cylindrical collecting electrode, l is the length of the cylinder, and Ω is the solid angle subtended by the segment of the spherical surface comprising the spherical collecting electrode. Introducing these expressions into Equation (13), integrating, and comparing with Equation (14), we see that

$$g_{1p} = (2r_c/A)^{1/2} \quad (29)$$

$$g_{1y} = [2 \ln(r_c/r_1)/\theta l]^{1/2} \quad (30)$$

$$g_{1s} = [(2/\Omega)(1/r_1 - 1/r_c)]^{1/2} \approx (2/\Omega r_c)^{1/2}. \quad (31)$$

The calculation of g_2 is more complicated. Only the final results will be given here (21):

$$g_{2p} = 2A/r_c^3. \quad (32)$$

A particularly simple solution to Equation (15) is obtained by assuming that the electric-field intensity close to the discharge electrode is effectively zero (90). In this case

$$g_{2p} = 9A/8r_c^{3*}, \quad (33)$$

which is of the same order of magnitude as the quantity in Equation (32).

The value of g_2 for cylinders has been derived in a number of different ways. The more rigorous approaches yield (66, 93)

$$g_{2y} = 4\ell^2/r_c^2 \ln(r_c/r_d). \quad (34)$$

The assumption of zero electric field near the discharge electrode results in (90)

$$g_{2y} = \ell^2/r_c^2, \quad (35)$$

roughly the same as Equation (34).

Again assuming zero electric field at the discharge electrode, we obtain for a spherical system (90)

$$g_{2s} = 3n/8r_c. \quad (36)$$

Finally, calculating g_4 (Equation (22)) from Equations (29) and (32)

$$g_{4p} = 2; \quad (37)$$

from Equations (29) and (33)

$$g_{4p} = 3/2; \quad (38)$$

from Equations (30) and (34)

$$g_{4y} = 2\sqrt{2} \ln(r_c/r_d); \quad (39)$$

from Equations (30) and (35)

*This solution is actually of the form $i = g_2 \epsilon_0 (V-V_s)^2$ as compared to our $i = g_2 \epsilon_0 V(V-V_s)$, but at high voltage $(V-V_s)^2 \approx V(V-V_s)$.

$$\epsilon_{hy} = \left[2 \ln^3(r_c/r_a) \right]^{1/2}; \quad (40)$$

and from Equations (31) and (36)

$$\epsilon_{hs} = (3r_c^3/4r_a^3)^{1/2}. \quad (41)$$

Pressure effects. It is shown by experiment and theory that the mobility of a gas over a wide range is

$$b = \rho_{go} b_o / \rho_g \quad (42)$$

where the subscript o designates standard conditions (66). Rewriting Equation (25) we have

$$\eta_o = (\epsilon_4 / \rho_{go} b_o) (\epsilon / k^3)^{1/2} \rho_g^{-1/2}. \quad (43)$$

The dielectric constant ϵ is sensibly constant over a wide range of gas densities (23). The efficiency, therefore, increases with density. We shall find that the efficiency is very low in atmospheric air and, for this reason, it will be of special interest to investigate blower operation at other than atmospheric conditions.

The density may be expressed in terms of the pressure and temperature (deg K)

$$\rho_g = \rho_{go} (p T_o / p_o T) \quad (44)$$

whence

$$\eta \approx (\epsilon_4 / b_o) (\epsilon T_o / \rho_{go} p_o k^3)^{1/2} (p/T)^{1/2}. \quad (45)$$

Ozone generation. The glow surrounding the emitting electrode of a corona discharge in air and certain other gases may constitute a region of significant chemical activity (36). In air, ozone and, to a lesser extent, oxides of nitrogen are formed. These gases are toxic to humans. 0.1 ppm of ozone in air is commonly accepted as the maximum allowable concentration for prolonged periods of exposure (96).

The rate at which ozone is generated in the electric discharge is a function of the current and the electrode geometry. Assume that for a given geometry this rate G (kg/sec) is given by

$$G = R i^2 \quad (46)$$

where R (kg-sec²/amp²) is a constant of proportionality. The resulting mass concentration of ozone, C_m (mass of ozone per mass of air), is

$$C_2 = R_1^2 / v_c A \rho_g. \quad (47)$$

The corresponding volume concentration, C_v (volume of ozone per volume of air), is

$$C_v = R_1^2 / v_c A \rho_2 \quad (48)$$

where ρ_2 is the density of ozone.

The concentration formulas above are valid for series and parallel combinations of identical blowers. In both cases i is the total current drawn by the multiblower system and A is the total cross-sectional area which, in a series arrangement, is unchanged. Eliminating the current between Equations (34) and (48), and setting $1/A g_1^{2a} = g_2 (n^{2a-1})$, we obtain

$$C_v = g_2 R (\rho_g / \rho_2) n^{2a-1} / \rho_2. \quad (49)$$

For $a > 0.5$ it is clear that any attempt to dilute the ozone by increasing the air-flow rate will be futile.

The difficulty existing when $a > 0.5$ is, to some extent, remediable. As seen from Equation (49) that it is then possible to reduce the ozone concentration at constant volumetric flow rate by working several individual blowers in parallel, each at reduced capacity. Specifically, a required volumetric flow v_1 (m³/sec) can be provided by a single blower of capacity v_A or by n identical parallel blowers each moving air at the velocity v/n . The parallel assembly has a cumulative cross-sectional area nA . Since the ozone concentration is the same for the system of blowers as for any individual in it we have, for the system,

$$C_v = g_2 R (\rho_g / \rho_2) n^2 (v/n)^{2a-1} / \rho_2. \quad (50)$$

The ozone concentration has now been diminished by a factor of n^{1-2a} .

The efficiency in terms of the number of parallel units may be obtained from Equations (17) and (23),

$$\eta = \frac{g_4}{5} \left(\frac{\epsilon}{\rho_K^3} \right)^{1/2} \left\{ 1 - \frac{2}{1 + \left(1 + \frac{\rho_g^2 R}{g_c \epsilon n^2 v_s^2} \right)^{1/2}} \right\}^{1/2} \quad (51)$$

where $g_3 = g_3^2 A^2$ and $U = uA$, the total volumetric flow rate. It is seen that reducing the ozone concentration in the manner described will also bring about a decrease in efficiency.

blowers in series. If the pressure developed by a single blower is small, or the back pressure of the external load large, it is of particular interest to investigate the advantage of stacking blowers in series. Let each blower in the series assembly generate a pressure p . The whole assembly then generates pressure np . This forward pressure must overcome the internal back pressures of each blower p_B .

$$p_B = K_B \rho_g v_c^2 / 2 \quad (52)$$

where K_B is the internal loss coefficient of a single blower. The forward pressure must also accommodate an external load or back pressure

$$p_L = K_L \rho_g v_c^2 / 2 \quad (53)$$

where K_L is the loss coefficient of the external load. We have then

$$np = np_B + p_L = nK_B \rho_g v_c^2 / 2 + K_L \rho_g v_c^2 / 2 \quad (54)$$

or

$$v_c = \left[p / \rho_g (K_B + K_L/n) \right]^{1/2}. \quad (55)$$

The total loss coefficient $K_B + K_L/n$ here corresponds to the coefficient K in Equation (8). Consequently, we may write, by comparison with Equation (14),

$$v_c = C_1 \left[1 / \rho_g b (K_B + K_L/n) \right]^{1/2} \quad (56)$$

where C_1 is the constant due to a single blower.

EXPERIMENTAL RESULTS AND DISCUSSION

blower design. Most of the experimental data to be reported were obtained using an electrostatic blower not conforming in design to any of the geometric configurations already described. The discharge electrode in this blower (Figure 1) consists of a needle point, the tip of which is concentric with a wire screen serving as the collecting electrode. The electrodes are housed in an insulating cylinder. Unless so stated to the contrary, all measurements hereafter given were obtained with a negative discharge with this blower in atmospheric air. The blower is not of the concentric spherical type described above since the same boundary conditions are not imposed aerodynamically as well as electrically. It is, however, simpler to construct and does give an idea of the extent to which the mathematical assumptions already made can be violated without seriously impairing the validity of the forms of the derived equations. Other experimental designs will be described later. The behavior of miniaturized blowers meeting assumed boundary conditions has been considered by Stuetzer (90, 91, 92).

Effect of fluid flow on current. In the foregoing equations dependent on Equation (7) it is assumed that $v \ll bE$. This is equivalent to saying that the current

$$I = \int j dA = \int \rho(v + bE) dA \quad (57)$$

is essentially independent of the gas velocity. The truth of this assumption is examined in Figure 2. Current is given as a function of average air velocity. Along the broken curve air motion is produced solely by the mechanism of the electric wind. An external fan provides the pressure required to reach other velocities. The current is constant over a velocity range extending well beyond the maximum attained by the electric wind.

Tests with electrodes of several different geometries and sizes give results similar to those of Figure 2.

In insulating liquids, because the ion mobility is about 10^{-2} as great as it is for gases (93), v is no longer negligible relative to bE and the assumption of constant current is not tenable.

The fluid velocity v which may influence the current is not necessarily the average fluid-flow velocity, particularly when an abrupt barrier exists in the fluid path. This fact is borne out by an experiment in which the needle-screen blower is mounted vertically, as shown in Figure 3 and used to pump transformer oil. The dashed increase in current accompanying

the moving oil is too much to account for in terms of the average oil velocity. It is readily observed, however, that circulatory oil currents are set up in the space between the discharge electrode and the free surface of the liquid. These oil currents provide a higher flow velocity just above the needle than near the walls of the tube. The circulatory velocity can be much higher than the average velocity by virtue of which the oil overflows its container. If, at the same time, the current density is greater along the axis of the tube than near its walls, the current must increase with the increasing circulation accompanying a rise in average velocity. That the current density does vary in this manner was, years ago, experimentally confirmed by Chattock (16) for a point discharging onto a plane and more recently by Heiser and Harze (44, 45) for a point discharging onto the concave surface of a sphere.

Circulatory gas currents can be produced in a blower by partially or completely obstructing the flow of gas upstream of the discharge electrode, but this has no pronounced effect on the electric current at electric-wind velocities. It should be pointed out, however, that judiciously designed constructions in the flow path, rather than beyond, the discharge electrode may serve to eliminate, and not induce, wasteful eddies in the moving fluid (90, 92).

Current as a function of voltage. The corona starting voltage V_3 of Equation (16) has no precise physical significance, but is an indispensable parameter for computational purposes. Its value is readily obtained by noting that, since $1/V$ is a linear function of the voltage, V_3 is the V intercept. The slope of the straight line is g_2/V_3 . The geometric function g_2 can, therefore, be immediately determined. Figure 4 shows that the measured current is greater, at higher voltages, than the current-voltage equation indicates. This is a consequence of the assumption of constant mobility and does not lead to error serious enough to invalidate our subsequent results.

Velocity. Equation (14) predicts that the velocity of the electric wind will be proportional to the square root of the current. This expectation is supported by the experimental data (Figure 5). The velocities reported in all cases are average values obtained by traversing the diameter of the blower duct with a Pitot tube or hot-wire anemometer. Quality of turbulence in the air stream affects these devices differently with the result that identical average velocities may produce strikingly variant velocity readings on the two instruments. In order to reduce such discrepancies as much as possible the Pitot tube and anemometer were calibrated against an orifice flowmeter which was used as a standard.

The term $g_1/k^{1/2}$ is obtained from the slope of the line of Figure 1. This, in combination with the values of g_2 and V_3 previously established, now enables us to calculate any of the quantities current, voltage, velocity, power and efficiency in terms of the others. A principle $g_1/k^{1/2}$, g_2 and V_3 can

be determined for a given blower simply by measuring the current and velocity corresponding to a single arbitrary voltage, V/V_0 , not too close to sparkover.

Air velocity as a function of voltage is shown in Figure 6. The solid line represents Equation (17) using the value $\epsilon_1/K^{1/2}$ already known from experiment. It is seen that the curve is almost linear, closely following Equation (18).

For completely formed stable ions in an electric field the intensity of which is not too high, the ion mobility is a constant independent of the field and of the coordinate r . We have assumed this to be the case in Equation (13). Properly, it is not field strength alone, but the field strength/ambient pressure ratio that furnishes the required criterion. The critical value of this quantity for air at room temperature is about 1.6×10^6 (v/m)/atm (66).

Efficiency. In most practical applications the efficiency of electrokinetic conversion is of primary concern. For a set geometry Equation (25) reveals that the efficiency is proportional to $\epsilon^{1/2}/\rho^{1/2}$. In a negative discharge in atmospheric air this quantity is equal to 0.014, but for liquids it is much larger. Thus, for kerosene, $b \approx 3 \times 10^{-7}$ (m/sec)/(v/m) (90), $\rho = 750 \text{ kg/m}^3$ (ρ_g in this case, is the liquid density) and $\epsilon = 1.8 \times 10^{-11}$ Farad/m, whence $\epsilon^{1/2}/\rho^{1/2} \approx 0.5$. In general, the efficiency of a liquid pump will exceed that of the corresponding gas pump by one or two orders of magnitude. In view of this, low gas blower efficiencies should be anticipated. Values of the order of one percent have been reported for a number of electrode arrangements (27, 41, 92).

Efficiencies calculated on a purely theoretical basis are of interest for comparative purposes. The following table is obtained from Equations (25), (37), and (38) for parallel-plate blowers in room air. The loss coefficient will vary with duct design, but in no case will be less than $K=K_5=1$. Positive and negative ion mobilities are 1.4×10^{-4} and 2.0×10^{-4} (m/sec)/(v/m) respectively.

K	$\eta, \%$			
	- ions		+ ions	
	$\epsilon_L = 2$	$\epsilon_L = 3/2$	$\epsilon_L = 2$	$\epsilon_L = 3/2$
1	0.1	2.1	3.0	2.5
2	1.0	0.7	1.0	0.9
3	0.1	0.4	0.7	0.5

Blowers of this type, it seems, are inherently limited to efficiencies of the order of one percent. Cylindrical geometry does not materially affect this disappointingly low value. Although g_y calculated from Equations (39) or (40) can be an order of magnitude greater than g_{4p} (taking $r_c/r_d = 10^2$ or 10^3), the greater loss coefficient of the wedge-shaped duct compensates for this in terms of efficiency. Similar considerations apply for a spherical system.

Figure (7) gives the experimental data and theoretical curve (Equations (21) and (23)) matching output and input powers in the needle-screen blower under consideration. The changing slope indicated by Equation (23) is not evident in the curve. Although efficiency is sensitive to voltage changes at low voltage, low voltage yields very low power, with the result that the expected dip in the curve occurs too close to the origin to be noticed. Plotting efficiency as a function of voltage in Figure 8 the sought-after effect becomes apparent. The curve is that of Equation (23). The sharp deviation from theory in the neighborhood of 20 kv is easily explained. Since efficiency is proportional to v^3 relatively small instrumental errors in measuring velocity are grossly magnified in efficiency calculations. Note the experimental velocity readings between 15 and 25 kv in Figures 5 and 6.

Pressure and density effects. It was shown above that since the product $\rho g b$ is independent of the pressure, the gas velocity as given by

$$v_c = g_1(1/\rho g b K)^{1/2} \quad (14)$$

must also be independent of the pressure. In order to confirm this behavior the velocity output of a needle-screen blower was measured in air at room temperature, over a range of ambient pressures from a fraction of an atmosphere to 8 atm. The current was held constant at several pressure levels by adjusting the voltage as the pressure varied. The results are reproduced in Figure 9. For air $\rho g b$ is 2.4×10^{-4} coul-sec/m³. Figure 5 gives $g_1/K^{1/2} = 2.79 \text{ m}^{-1/2}$. Using these values Equation (14) yields $v_c = 180 i^{1/2}$, a relation closely followed by the data.

As the pressure is raised the ion mobility decreases causing the current at a given voltage to fall. In order to maintain a constant current the applied voltage must be raised with the pressure. Although the sparkover voltage increases with the pressure it does not rise fast enough to permit a constant current to be maintained without exceeding sparkover. Consequently, the lines of constant velocity are bounded at high pressures as shown. With decreasing pressure the sparkover voltage drops more rapidly than does the applied voltage required to sustain the constant current. Lines of constant velocity are, therefore, bounded by sparkover on the low pressure side also. The described effect is illustrated in Figure 10.

Equation (43) reveals that efficiency increases with gas density. It is important to note, in this connection, that mere pressurization, without regard to temperature, may not be sufficient to raise the efficiency. It is not the pressure per se but the density which is the governing factor. We observe from Equation (45) that operating at atmospheric pressure and reduced temperature increases efficiency.

The product $\rho_g b$ has an approximately constant value for a given gas, i.e. it is independent of density, ambient pressure and temperature. It follows at once from Equation (14) that the velocity of the electric wind is likewise independent of these three quantities. Changes in efficiency brought about by manipulating pressure or temperature result from altering the density and with it the mass of gas moved per unit time.

As the temperature varies the accuracy of Equation (44) must not, in all cases, be insisted upon. Thus, the mobility rises linearly with temperature at constant pressure but at best is only approximately constant as the temperature changes at constant pressure (66).

Equation (42) has been roughly verified for most gases at room temperature at pressures extending from about 75 to about 0.2 atm. Above this range the mobility of negative ions decreases and below it increases rapidly. It appears that at high pressures many ions consist of several molecules bound together, the combination having a correspondingly higher mass and, therefore, lower mobility. At low pressures the negative ions most likely exist largely as highly mobile free electrons (68).

According to Equation (14) the velocity is inversely proportional to $(\rho_g b)^{1/2}$. Figure 11 illustrates the extent to which this quantity varies among a number of gases. Ammonia and very pure argon are separated by three orders of magnitude. The reduction in mobility caused by impurities is probably to be explained by the impurities becoming attached to ions and forming large slower moving molecular clusters. Inert gases like helium and argon, if extremely pure, pass a current of high-velocity electrons. Oxygen and other electronegative gases, even when pure, show a strong affinity for electron attachment and, as a result, have much lower mobilities than the pure inert gases (19).

In order to achieve maximum output power an electrostatic blower must be operated at maximum input power, i.e. at voltages just below sparkover. Operation during sparkover results in lowered gas velocity. This is likely due to the fact that sparking not only produces mobile free electrons, but also confines the current to a very small region of the total volume between the electrodes.

Increasing the density of a gas will, except at sufficiently low densities, raise the sparkover voltage. Operating close to sparkover we have $V_{sp} \gg V_g$, where the subscript sp designates the maximum pre-sparkover voltage. Equations (17) and (20) then yield the convenient approximations $V_{csp} \propto V_{sp}$ and $P_{csp} \propto V_{sp}^3$.

Experimental velocity, power and voltage data just below sparkover are shown as functions of gas density in Figure 12. The smooth curves of velocity and power represent Equations (17) and (23) respectively. Efficiency at sparkover is, by Equation (25), proportional to $\rho_g^{1/2}$. This relationship is borne out by Figure 13.

The quantities g_1 through g_6 are, by definition, functions of geometry only. Accordingly, they must remain fixed for a given electrode arrangement regardless of electrical conditions or the nature of the gas. In considering the affects of pressure we have made certain assumptions concerning the variation of mobility with density. At low enough densities, however, for reasons already given, these assumptions fail. We shall now determine at what point and to what extent this occurs.

The functions g are all defined in terms of g_1 , g_2 , and A . It will, therefore, suffice to examine g_1 and g_2 alone. We do this by placing no limits on the validity of Equation (42) and then observing the apparent changes in g_1 and g_2 as the density varies. The experimental results calculated from Equations (14) and (16) for a needle-screen blower in air appear in Figure 14. The quotient $g_1/K^{1/2}$ rather than g_1 alone is given since the former is more readily measured. $g_1/K^{1/2}$ and g_2 are both constant at densities down to about atmospheric. Below this level $g_1/K^{1/2}$ falls to zero and g_2 increases rapidly. These variations result from the assumption that b remains proportional to $1/\rho_g$ at low ρ_g . In reality, b rises faster in this region than does $1/\rho_g$, and this disproportionate increase is, by Equation (14), reflected as a decrease in $g_1/r^{1/2}$. Similarly, by Equation (16), g_2 must rise.

Some blower variables are more sensitive to apparent variations in the g 's than are others. Thus, the expected dips in the constant-current curves of Figure 9 are clearly in evidence. On the other hand, the experimental powers, voltages and velocities of Figure 12 seem to follow the theoretical values well even at low gas densities.

The inconstancy of the g 's below a certain density does not affect the usefulness of the general theory below that

density. At low densities Equation (42) and the relations containing it should be disregarded and appropriate values of mobility be introduced into the theory directly and not as functions of density.

Ozone generation. Equations (47), (48), and (49) assume that the rate of ozone generation for a given geometry is proportional to a power of the current. Experimental support for this hypothesis is offered in Figure 15. Ozone concentration was determined by the potassium-iodide method of Britt (12).

Electrostatic precipitators designed to filter air for human consumption commonly employ a positive discharge since reason exists for believing that such polarity will yield a lower ozone output (36, 106). Similar considerations evidently do not apply to the needle-screen blower. Contrary to expectation, we observe from the curves that positive corona generates ozone at several times the rate of negative corona. The negative curve for a single blower is fitted by the following form of Equation (46):

$$G = 0.1 i^2. \quad (49)$$

Day-to-day variations in the data are, perhaps, attributable to fluctuations in atmospheric conditions (97).

A blower operating with negative corona near sparkover generates about 0.8 ppm by volume of ozone in air, a quantity in excess of the usual acceptable limit. This ozone concentration may be reduced at constant volumetric flow rate by adopting the arrangement of parallel blowers described above. Experimental and calculated data for such a case are shown in Figure 16. Ozone concentration measurements were actually made with a single blower over a range of currents; for this reason experimental points corresponding to fractional blowers appear. In Figure 16 the assumed parallel system is taken to have a constant volumetric flow rate of 1.54×10^{-2} m³/sec, the maximum delivered by a single blower. The drop in ozone concentration as blowers are added in parallel is striking. Two blowers produce 13 percent of the concentration of a single blower and five blowers only 0.8 percent of that amount. The efficiency loss accompanying a large decrease in ozone concentration is small.

Polarity. We can generally expect performance to be dependent on the choice of polarity of the discharge when the ionic mobility appears in the governing equations. In

atmospheric air the mobility of stable negative ions is 2.0×10^{-4} (m/sec)/(v/m) and that of stable positive ions 1.4×10^{-4} . Inserting these values into Equations (13) and (23) we find that $v_c^+ \approx 1.1 v_c^-$ at constant current and that $\eta^+ \approx 1.4 \eta^-$. The force on an ion in an electric field depends, of course, only on its charge and on the intensity of the field. A slowly moving ion exerts its drag force on the gas through which it is migrating over a longer period of time than an ion of high mobility. Hence, at a given current, the momentum ($\int F dt$) transferred to the gas by slow ions will be relatively greater. In consequence $v_c^+ > v_c^-$ and $\eta^+ > \eta^-$ as above. Ozone concentration C_v at constant velocity is, by Equation (49), proportional to Rb^2 . In the needle-screen blower a reversal of polarity will cause R and b to change in opposite directions. Variation, if any, of the exponent a in Figure 15 is not clear. Nevertheless, if minimum C_v is desired at a given output, positive corona remains preferable.

According to Equation (17) velocity is independent of polarity for a given voltage if the small effect of the corona starting voltage is neglected. This is shown experimentally in Figure (17). Sparkover during negative operation occurs at about 1.8 times the positive sparkover voltage. Since the kinetic power delivered at sparkover is approximately proportional to the cube of the sparkover voltage (Equation (54)) a single negative blower can produce the power output of six positive units.

The streamer theory of sparking has been proposed in order to explain the higher negative sparkover voltage (66). According to this, sparkover is initiated at the positive electrode. If this electrode is also a region of high electric intensity, i.e. if it is a discharge electrode, sparkover is then doubly facilitated. Sparkover in a negative discharge is retarded because the spark streamer must originate at the positive low-field electrode.

Blowers in series. Equation (56) predicts the velocity to be expected from a series arrangement of blowers working against a load. For simplicity, we shall continue to assume that the loss coefficients are independent of velocity. Screen coefficients are, however, known to increase at low enough velocities (48). At normal operating voltages such low velocities result from large external loads. In that case K_L/a is likely to be so much larger than K_B that departures from the "constant" value of the latter do not materially affect the velocity calculated from Equation (56).

Figure 18 shows the velocity output of five blowers in series as a function of the external load per blower. Since the blower assembly is designed with a low-loss inlet and a

re-entrant outlet the minimum possible value of K_L is unity. The characteristic g_1 of each of the five needle-screen blowers employed in the series test is, for an undetermined reason, significantly lower than in the preceding cases. Because of this, the output of the assembly does not exceed that previously obtained for an individual unit.

The increase in velocity per additional series blower is small. Setting $K_L=1$ we note from Figure 18 that a five-blower assembly delivers 3.5 m/sec of air as against 3.0 m/sec for a single blower.

Velocity profiles. In measuring gas velocities it must not be assumed that because of the turbulence created by the corona wind an approximately flat velocity profile exists across the diameter of the blower. Serious errors are introduced if center-line velocities measured close to the discharge point are considered representative of the turbulent cross section.

Velocity profiles for the needle-screen blower are shown in Figure 19. A relatively high-speed gas movement is generated along the axis of the discharge electrode. Hence, the resulting velocity profile is especially steep close to the point. Further away the profile assumes the flat shape typical of turbulent flow. As the voltage is reduced all profiles, regardless of distance from the discharge, tend to assume the same relatively flat form.

The velocity profile is noticeably dependent on the electrode geometry, i.e. the electrodes exhibit a focussing property. Thus, if a ring alone is used as the collecting electrode in Figure 1, transfer of momentum in the axial direction is reduced and the profile flattens.

Geisler (44) reports that the profile for a needle-plane screen system has the form of a normal distribution.

Other electrode geometries. The experimental results described above have almost all been obtained using the needle-curved screen blower shown in Figure 1. Many of the experiments have, however, been repeated for electrode configurations of other sizes and designs, viz: wires and plane screens, wires and rods, points and plane screens, points and rings. Except for the anticipated variations in the constants g and K the results are similar to those already given. Agreement of the theory with the experimental data of other investigators employing various electrode arrangements is, in general, good. For example, Harney (51) in an experiment similar to that of Figure 2, finds corona current a somewhat more sensitive function of air velocity, but still not

sufficiently so to be of consequence at electric wind velocities. Linear velocity-current^{1/2} curves (Figure 5) are also reported elsewhere. Ladenburg and Tietze (57), in examining the role of the electric wind in the electrical precipitation process, note such a velocity current dependence for point-plane and concentric cylindrical electrodes. The form of Equation (17) is supported by the results of Heiser (44) for a point discharging into the interior of a sphere but, oddly, not for a point discharging against a plane. Several of the foregoing relationships are corroborated by the experiments of Stuetzer with liquids in a plane parallel system (90, 92). Additional supporting data is found in references 1, 16, 45, 65, and 76.

CONCLUSIONS AND RECOMMENDATIONS

An approximate theory has been developed relating the electrical and mechanical parameters of an electric-wind blower. Although derived for specific boundary conditions, the forms of the equations are found to be widely applicable and should be useful in predicting the performance of electrostatic blowers of a number of diverse geometries, provided only that two geometric constants are determined experimentally.

Complete lack of moving parts gives the electrostatic blower advantages over conventional fans: vibrationless, almost silent operation; absence of gyroscopic and other rotational effects; no lubrication requirements; minimal replacement due to wear (discharge electrodes). The chief disadvantages of the blower are the very low efficiency of energy conversion and, in certain cases, the generation of extraneous gases in the corona discharge, e.g., ozone in air. The theory, as developed, offers no hope for a radical breakthrough in overcoming either obstacle. Nevertheless, limited success can be expected by careful geometric design, e.g., improving efficiency by controlling the g 's and K 's or reducing ozone by parallel operation.

Several areas of interest suggest themselves for future investigations: contamination of the gas with dust or high-molecular-weight (i.e. low-mobility) ions, pulse or a-c energization, further study of the g 's as functions of geometry, combination of the blower with an electrical precipitator. Brief looks have been taken at each of the foregoing; adequate data is not available to warrant conclusions at this time.

ACKNOWLEDGEMENTS

The author is grateful to Mr. John Jarema who made many helpful suggestions, constructed the experimental equipment and took large numbers of measurements. Messrs. Robert Brown and George Robertson assisted in the ozone determinations.

NOMENCLATURE

A = cross-sectional area, m^2
 b = ion mobility, $(m/sec)/(v/m)$
 c = rms velocity of molecules, m/sec
 C_m = mass concentration of ozone, dimensionless
 C_v = volume concentration of ozone, kg/m^3
 d = diameter of screen wire, m
 E = electric field strength, v/m
 f = friction factor of duct, dimensionless
 g_1 = function of geometry, $m^{-1/2}$
 g_2 = function of geometry, m^{-1}
 g_3 = function of geometry, m^{-1}
 g_4 = function of geometry, dimensionless
 g_5 = function of geometry, m^{-1}
 g_6 = function of geometry, m^2
 g_7 = function of geometry, m^{-1}
 i = current, amp
 j = current density, amp/m^2
 k = function of gas, $coul/m$
 K = total aerodynamic loss coefficient, dimensionless
 K_1, \dots, K_6 = aerodynamic loss coefficient, dimensionless
 K_B = internal loss coefficient of a single blower, dimensionless
 l = length of cylindrical electrodes, m
 M = mass, kg
 n = number of blowers in series or parallel, dimensionless
 p = pressure, $newton/m^2$
 p_B = internal back pressure of a single blower, $newton/m^2$
 p_0 = standard reference pressure, $newton/m^2$
 P_i = electrical power input, w
 P_o = kinetic power output, w
 P_{opp} = maximum pre-sparkover kinetic power output, w
 r = distance from origin of coordinates, m
 r_c = coordinate of collecting electrode, m
 r_d = coordinate of discharge electrode, m
 R = rate of ozone generation, $kg/coul$
 Re = Reynolds number, dimensionless
 s = separation of screen wires, m
 t = time, sec
 T = temperature, $deg K$
 T_0 = standard reference temperature, $deg K$
 U = total volumetric flow rate of parallel assembly, m^3/sec
 v = wind velocity, m/sec
 v_c = wind velocity at collecting electrode, m/sec
 v_{opp} = maximum pre-sparkover wind velocity at collecting electrode, m/sec
 v_{ion} = ion velocity, m/sec
 V = voltage, v
 V_0 = apparent corona starting voltage, v

V_{sp} = maximum pre-sparkover voltage, v
 ϵ = absolute dielectric constant, farad/m
 η = fractional efficiency of electrokinetic conversion, dimensionless
 η_0 = asymptotic fractional efficiency of electrokinetic conversion, dimensionless (Eq. (45))
 θ = plane angle subtended by segment of cylinder forming collecting electrode, radians
 ρ = charge density, coul/m³
 ρ_g = gas density, kg/m³
 ρ_{go} = gas density at standard conditions, kg/m³
 ρ_z = ozone density, kg/m³
 ϕ = electric potential, v
 Ω = solid angle subtended by segment of spherical surface forming collecting electrode, radians

HISTORY OF THE ELECTRIC WIND

Earliest observations. Although the existence of an electrostatic force of attraction had been known to classical antiquity it remained for Niccolò Cabeo, an Italian Jesuit and contemporary of Galileo, to observe and record in 1629 the phenomenon of electrostatic repulsion (13). Cabeo noted that when light filings or sawdust were attracted to an electrified body, they would touch it and then be repelled. He explained this behavior on the supposition that a charged body produces an electrical effluvium which drives off the surrounding air and forms a circulatory wind which, on its return, blows entrained particles to the body with such force that the particles, in some cases, rebound. An electric wind was thus conceived in fiction before it was discovered in physical reality. A few decades later, Cabeo's hypothesis was conclusively disproved by the Irish natural philosopher Robert Boyle who demonstrated that electrostatic attraction was present in a vacuum as well as air (10).

The discovery of the electric wind could not have antedated the development of the high-voltage generating machine. A frictional machine consisting of a sulfur sphere mounted on a crankshaft was described in 1672 by Otto von Guericke better known for his invention of the vacuum pump and the Magdeburg hemispheres (39). The sulfur sphere was charged by rubbing the hand against it while it was rotated in a wooden frame. Using this apparatus, von Guericke made the important discovery of the effectiveness of pointed conductors in attracting charged bodies. He noted further that the rubbed globe glowed in the dark and that when it was brought to the ear, "roarings and crashings" were heard in it. This is the earliest recorded observation of the corona discharge; we find no mention, however, of an associated electric wind.

Von Guericke's frictional machine and subsequent improvements on it accelerated the advance of electrical science. In 1709, Francis Haukebee, curator of instruments for the Royal Society of London, reported that he had experienced a weak blowing sensation by holding a charged tube close to his face (43). Haukebee's announcement of his discovery throws interesting light on the state of electrical knowledge and experimental technique at the time. "Having procured a Tube ... of ... Glass ...," he wrote, "I rubb'd it pretty vigorously ... until it had acquired some Degree of Heat ... When the Tube became hottest by the strongest Attrition, the Force of the [electrical] effluvia was render'd manifest to ... [the] Sense ... of feeling. They ... were plainly to be felt upon the Face ... if the rubb'd Tube were held near it. And they seemed to make very nearly such sort of strokes upon the Skin as a number of fine

lumber hairs pushing against it ... This vigorous Action of the Effluvia put me upon an attempt, to find in what manner such a motion was propagated, and in what ... sort of track it went along. For which end I held the rubb'd Tube near the Flame of a Candle, Smoke, Steam, Dust and the surfaces of Liquids; but without any manner of success.

"The reason for which, I attribute to the impediments the Effluvia met with from these Bodies the Tube was plac'd near. For the small parts of Dusts and Powders, the steams of Liquids, the cleaginous Fumes of Flame, and the like sort of parts in Smoke it self immediately adher'd to the surface of the Tube, and so kept in the Effluvia: which therefore requir'd the assistance of a fresh Attrition to open their passage and give them vent again."

In the course of his investigation of the electric wind, Hauksbee had stumbled upon electrostatic precipitation, much the same as Beccaria, who is generally credited with the discovery, was to do some sixty years later.

Shortly after Hauksbee, Isaac Newton repeated the experiment (75). "The electric Vapour", he wrote, "... excited by the friction of the ... [Sphere] against the Hand will ... be put into such an agitation as to emit Light ... and in pushing out of the ... [Sphere] will sometimes push against the Finger so as to be felt." It may have been Hauksbee's work that called Newton's attention to the electric wind. The account quoted appears in the second edition of his "Opticks" but is lacking in the first, and in the interval Hauksbee's researches had been published.

In 1746, the distinguished French philosopher, Jean Antoine Nollet revealed his findings that electrified points displayed "brushes of light" (74). The following year, Benjamin Franklin reported in a letter to his friend, Peter Collinson of the Royal Society, "the wonderful effect of pointed bodies, both in drawing off and throwing off the electrical fire (88)." Nollet's and Franklin's observations were largely a rediscovery of a phenomenon earlier noticed by von Guericke and long since forgotten. In view of both these investigators' subsequent work with pointed conductors, it is surprising that their writings are silent on the electric wind (20, 99). At least Franklin, however, was familiar with it. Ebenezer Kinnersley, professor of English at the College of Pennsylvania and a close associate of Franklin had observed in 1752 that "you may feel the fire ... [a Point] discharges blow on your hand as a cool Wind (51, 52)."

Two years before Kinnersley's announcement, Benjamin Wilson, secretary to the Royal Society, described "the blast resembling wind [which] seems to arise from the particles of air being put into a violent rapid motion by the issuing of the electrical matter ... at points, edges, or angular terminations." Through

failure to obtain the electric wind in an exhausted vessel, Wilson proved that the wind is indeed what its name supposes it to be, not a movement due to "electrical matter" per se (108).

Adequate communication between the scientists of the period does not seem to have existed despite the not inconsiderable personal correspondence and publication of journals and monographs that is known to have occurred. It is amusing to read, time and again, of the presumably independent "discoveries" of the electric wind reported in the "Transactions of the Royal Society", the "Annalen der Physik" and sundry other publications, sometimes within only a few years of each other.

The electric fly. The possibility of employing the electric wind as the driving mechanism of an electrostatic motor occurred to a number of investigators over the years. In 1750 Wilson succeeded in producing rapid rotary motion of a pinwheel by directing against it the electric wind from a point discharge (108). Not long afterwards, Hamilton, Professor of Philosophy at the University of Dublin, reasoning that if a fixed point could move air a freely suspended point should itself move in (relatively) still air, modified Wilson's apparatus to a single-stage device (109). This, in its simplest form, consisted of an S-shaped wire suspended horizontally at its center point on a vertical conducting shaft. The ends of the "S" were sharpened to points from which the discharge took place when high voltage was applied to the shaft. The "S" would then spin about its axis. The "electric fly," as it was called in England (French: "tourniquet électrique," German: "electrischer Flugrad") quickly became a favorite experimental device among students of electricity. Diverse explanations of the fly's behavior were forthcoming on all sides.

Hamilton considered that "the electric particles, by their elastic force, issue directly forwards from the points, and endeavor to expand themselves, but meeting with some resistance from the air, force the wire to move backwards in a contrary direction - much in the same manner that a Catherine wheel is made to turn round in a direction contrary to that in which the small rockets attached to the periphery discharge themselves." Newton's Third Law had been published over eighty years earlier, yet it was still considered necessary to fall back on air resistance in order to explain the action of a rocket.

Using a negative rather than Hamilton's positive discharge, Kinnersley repeated the experiment in 1761 (52). He expected the fly to turn in the opposite direction as it should have on Hamilton's hypothesis, "but was extremely disappointed, for it still went the same way as before." Kinnersley attempted to account for this in the following curious manner: "When the

stand [supporting] the fly was electrified positively, I suppose that the natural quantity of electricity in the air being increased on one side by what issued from the points, the needle was attracted by the lesser quantity on the other side. When electrified negatively, I suppose that the natural quantity of electricity in the air was diminished near the points; in consequence whereof the equilibrium being destroyed, the needle was attracted by the greater quantity on the other side."

Joseph Priestly, the earliest historian of electrical science and celebrated discoverer of oxygen, in commenting on these experiments in 1767, remarked that the fly turning the same way, regardless of polarity, might be taken as a proof "that the electric fluid issues out at the points in both cases alike, and by the reaction of the air is together with the points driven backwards - contrary to what ought to have been the case if the electric fluid had really issued out of the points in the one case and entered in the other (80)."

In 1771, the Italian electrician-astronomer, Giambattista Beccaria, observed, "The celebrated question of why points drive the air forward, whatever the direction of the fluid, is reduced to the general fact that the electricity forces in opposite directions the resistance through which it passes." Beccaria associated a certain expansive force with electricity; the point was therefore driven back by the electricity thought to be expanding into the air (5).

We owe the correct explanation of the electric wind to the Anglo-Italian natural philosopher, Tiberius Cavallo who wrote in 1777 that the motion of the fly depended "upon the repulsion existing between bodies possessed of the same electricity; for whether the fly is electrified positively or negatively, the air opposite to the points of the wires (on account of the points easily transmitting electricity) acquireth a strong electricity analogous to that of the points; and therefore the air and the points must repel each other." This reasoning, he adds, "is confirmed by observing that the above fly not only does not move in vacuo, but even if placed under a close receiver it will turn for a little while and then stop; for the quantity of air contained in the receiver may become readily and equally electrified (15)."

This view was not, however, universally acceptable. Joseph Weber reassessed Beccaria's argument in 1791: "... The electrical matter traveling out of the points of the cross [i.e., the fly] impinges against the air as a resistive body ... and drives back the easily movable wires of the cross. In the negative case, the electrical matter passes into the points from the air, something that cannot happen without pressure being exerted against the points (105)."

John Cuthbertson, English "philosophical instrument maker" offered the valid explanation in 1807, ~~that the motion~~ of the fly "is occasioned by the action of the electric fluid against the electrified air near the point (25)."

Jean Baptiste Biot, professor of natural philosophy at the College de France, held, with Poisson, that electricity is retained on a body's surface by atmospheric pressure. On this basis, Biot maintained in 1816 that the motion of the fly could not be produced in a vacuum because the electricity of the fly would be instantly dissipated. In the air, on the other hand, motion could be readily produced if the points were sharp enough to enable the electricity to accumulate there and overcome the pressure of the atmosphere. Biot thought motion then resulted in much the same manner as in a common variety of rotating lawn sprinkler (6).

The retrogression in assigning a cause to the electric wind continued. The writer of the article "Electricity" in the Encyclopaedia Metropolitana, published about 1824, stated, "Each of these points will give off a current of electricity, which from the reaction of the resisting medium (the air), will cause the system of points to revolve backwards with considerable rapidity (9)."

The English physician Peter Mark Roget, secretary to the Royal Society, is today less remembered for his scientific researches than for his famous dictionary of synonyms (85). In a treatise on electricity published in 1832, Roget discussed the fly: "Currents of air always accompany the discharge of electricity, whether positive or negative, from pointed bodies; for each particle of air, as soon as it has received its electricity from the point, is immediately repelled by the body. These currents tend powerfully to increase the dissipation of electricity, by bringing in contact with the point a continued succession of particles of air that are not yet electrified and are, therefore, ready to receive a charge." After this clear statement of the phenomenon it is surprising that Roget proceeds with "Each of the points [of the fly] will give off a stream of electricity: this will remove a part of the pressure which the fluid would have exerted on that side if no efflux had taken place; but as the pressure of the fluid on the opposite side of the wire in the opposite direction still operates in full force, the wire will be impelled in the direction of that force, that is, in a direction opposite to that of the stream." Roget goes on to describe an "electrical orrery," "an apparatus consisting of wires terminating in points, and having balls annexed to them to represent the planets ... constructed so as to revolve when electrified; and thus to imitate the planetary motions."

A similar explanation was offered in 1834 by Antoine Cesar Becquerel, professor of physics at the Musée d'Histoire Naturelle

and grandfather of Antoine Henri Becquerel, discoverer of radioactivity: "The experiment of the electric fly shows that the motion of bodies in electrical phenomena is really due to the difference in pressure which the air exerts on all the points of these bodies ... The electricity escaping by the points, the pressure exerted by the air on the extremities being greatly diminished, the needle turns in a contrary direction (6)."

The mechanism of the electric fly was also considered by Despretz (1837) (28), Lardner (1841) (58, 59), Harris (1851) (42), de la Rive (1853) (60), Pouillet (1856) (79) and Wiedeman (1865) (107), all of whom advocated the recoil explanation. Contrary to the opinion of the others who held that the mechanical reaction resulted from the efflux of electrical matter at the points, Wiedeman believed the discharge of metallic vapor to be responsible. Riess (1853) (84), Genot (1857) (35), Eisenlohr (1860) (31) and Tomlinson (1864) (99) maintained the theory of mutual repulsion between the electrified points and the air. Tomlinson experimented in both air and dielectric liquids and alone among numerous investigators claimed to observe rotation in either direction!

In 1897, Svante August Arrhenius, the Swedish Nobel laureate whose name usually brings to mind the theory of electrolytic dissociation, measured the intensity of the electric wind of a point discharge for several gases over a range of ambient pressures (1). Arrhenius noted the swing of an electric fly so constructed it could deflect under torsion but not rotate freely. In permanent gases the deflection of the fly, a measure of the pressure of the electric wind, was found to be proportional to the ambient pressure of the gas and, for different gases, to vary as the square root of the molecular weight. The reason for this became clear within the next few years with the demonstration by Chattock (17) that the pressure of the electric wind varied inversely with the mobility, the latter quantity in turn depending on the ambient pressure and molecular weight in such a way as to give the observed results.

Faraday and Maxwell. Michael Faraday's observations on the electric wind were published in 1838 as part of a more general study of the electrical discharge in gases and liquids. Faraday pointed out that "the part [of the air] which is charged may be but a small portion of that which is ultimately set in motion", implicitly recognizing that the electric wind is a momentum transfer process by friction or collision between charged and uncharged gas particles. Faraday extended his experiments to dielectric liquids and reported, "When the phenomena of currents are observed in dense insulating dielectrics, they present us with extraordinary degrees of mechanical force. Thus, if a pint of well rectified and filtered oil of turpentine be put in a glass vessel, and two wires be dropped into it in different places, one leading to the electrical machine and the other to the discharging train, on working the machine the fluid will be thrown

into violent motion throughout its whole mass, whilst at the same time it will rise two, three, or four inches up the machine side, and dart off in jets from it into the air (33)."

James Clerk Maxwell attached great importance to the study of gaseous discharge phenomena. He wrote, prophetically, that when such processes "are better understood they will probably throw great light on the nature of electricity as well as on the nature of gases ...". Since in Maxwell's time the gaseous discharge was not amenable to even rudimentary mathematical treatment, he confined his discussion of the subject in his classical "Treatise on Electricity and Magnetism" to a few pages. Interestingly, half this space was devoted to an account of the electric-wind. Maxwell's qualitative analysis of the wind mechanism was the most complete then written, and even today retains much of its validity. For this reason it is worth quoting at length (69):

"... When a conductor having a sharp point is electrified, the theory, based on the hypothesis that it retains its charge, leads to the conclusion that as we approach the point the superficial density of the electricity increases without limit, so that at the point itself the surface-density, and therefore the resultant electromotive intensity, would be infinite. If the air, or other surrounding dielectric, had an invincible insulating power, this result would actually occur; but the fact is, that as soon as the resultant intensity in the neighborhood of the point has reached a certain limit, the insulating power of the air gives way, so that the air close to the point becomes a conductor. At a certain distance from the point the resulting intensity is not sufficient to break through the insulation of the air, so that the electric current is checked, and the electricity accumulates in the air around the point.

"The point is thus surrounded by particles of air charged with electricity of the same kind as its own. The effect of this charged air round the point is to relieve the air at the point itself from part of the enormous electromotive intensity which it would have experienced if the conductor alone had been electrified. In fact, the surface of the electrified body is no longer pointed, because the point is enveloped by a rounded mass of charged air, the surface of which, rather than the solid conductor, may be regarded as the outer electrified surface.

"If this portion of charged air could be kept still, the electrified body would retain its charge, if not on itself at least in its neighborhood, but the charged particles of air being free to move under the action of electrical force, tend to move away from the electrified body because it is charged

with the same kind of electricity. The charged particles of air therefore tend to move off in the direction of the lines of force and to approach those surrounding bodies which are oppositely electrified. When they are gone, other uncharged particles take their place round the point, and since these cannot shield those next the point itself from the excessive electric tension, a new discharge takes place, after which the newly charged particles move off, and so on as long as the body remains electrified.

"In this way the following phenomena are produced: At and close to the point there is a steady glow, arising from the constant discharges which are taking place between the point and the air very near it.

"The charged particles of air tend to move off in the same general direction, and thus produce a current of air from the point, consisting of the charged particles, and probably of others carried along by them. By artificially aiding this current we may increase the glow, and by checking the formation of the current we may prevent the continuance of the glow.

"The electric wind in the neighborhood of the point is sometimes very rapid, but it soon loses its velocity, and the air with its charged particles is carried about with the general motions of the atmosphere, and constitutes an invisible electric cloud. When the charged particles come near to any conducting surface, such as a wall, they induce on that surface a charge opposite to their own, and are then attracted towards the wall, but since the electromotive force is small they may remain for a long time near the wall without being drawn up to the surface and discharged. They thus form an electrified atmosphere clinging to conductors, the presence of which may sometimes be detected by the electrometer. The electrical forces, however, acting between large masses of charged air and other bodies are exceedingly feeble compared with the ordinary forces which produce winds, and which depend on inequalities of density due to differences of temperature, so that it is very improbable that any observable part of the motion of ordinary thunder clouds arises from electrical causes ...

"The electrical glow is therefore produced by the constant passage of electricity through a small portion of air in which the tension is very high, so as to charge the surround particles of air which are continually swept off by the electric wind, which is an essential part of the phenomenon."

Means of rendering the electric wind visible. Becquerel, in 1871, followed the course of the electric wind by observing the flow lines of the smoke of burning phosphorus at the discharge point (5).

Another method for rendering the electric wind visible was given in 1786 by Cuthbertson (24). He placed a piece of heated camphor on a discharge point and formed, by the joint action of air currents and condensing vapor, moss-like camphor dendrites.

Exploration of the electric wind by noting the deflection of a small flame in the path of the air stream has been occasionally employed. Observations are complicated by the ionized structure of the flame. A candle flame, for example, is positively charged and will consequently be attracted and repelled at the same time by a negative discharging point. The candle technique is old; it was used by Cavallo (14) and Cuthbertson (25, 26) in 1777 and by Remer in 1801 (83).

In 1868, Töpler extended the earlier smoke-tracer method for rendering visible the flow pattern of the electric wind by introducing a schlieren technique (100). He wrote, "an unvarnished boxwood rod with rounded ends was attached to the electrical machine and its free end brought near to a grounded wire sphere ... When the arrangement in front of the main lens system of the optical apparatus was examined at constant light intensity, a shimmering air movement, flame-like in appearance, was observed between the rod and the sphere." Töpler demonstrated that the electric wind was not quite the "cool wind" of Kinnorsley, for if the air had not been warmed by the glow, differences in refractive index required for the schlieren effect would not have existed.

It was shown by Warburg in 1902 that under certain circumstances the electric wind could be made luminous (102, 103, 104). Warburg demonstrated that gas set into motion by a negative discharge in oxygen-free nitrogen underwent chemical change at the discharge electrode. The phosphorescence accompanying the return of the gas to its original state rendered it visible and so exhibited the pattern of the flow.

More recently (1930) Ladenburg and Tietze employed schlieren photography in connection with a jet of carbon dioxide gas introduced into the air in the region of the discharge (57). The direction and turbulent character of the electric wind was easily displayed.

The dust controversy. Until about the last quarter of the nineteenth century it had been commonly taken for granted that air particles were capable of electrification or, as we would say, gas molecules are capable of ionization. Coulomb (22) who in 1785 investigated the loss of electricity from a charged body suspended by insulating strings thought that after allowing for leakage along the supports, some lost charge still remained to be accounted for by a convective discharge through the air. Convective discharge or electrical convection were the terms applied to the passage of electricity from one place to

another by the motion of charge-bearing particles of ordinarily uncharged matter, e.g., gas molecules, dust, etc. Coulomb supposed that air particles in contact with a charged body acquired an electrical charge of the same sign as the body and that the particles were then repelled by the body. Accordingly, molecules of air could be charged with electricity, much like bits of metal.

Here and there an occasional question was raised regarding the validity of this charging theory. Faraday, though voicing some reservations, went along with the prevailing belief. Kinnersley and Franklin had objected more strongly. As Priestly tells us "Mr. Kinnersley of Philadelphia, in a letter dated March 1761, informs his friend and correspondent Dr. Franklin, then in England, that he could not electrify anything by means of steam from electrified boiling water; from whence he concluded that, contrary to what had been supposed by himself and his friend, steam was so far from rising electrified that it left its share of common electricity behind (52, 80)."

In time, however, experimental data accumulated which seemed to be explicable only on the hypothesis that molecules of gases or vapors resisted electrification. Warburg in 1872, supported by Mahrwold in 1887 adduced compelling evidence that the loss of charge from an isolated electrified body could be accounted for by the presence of dust in the ambient air (73, 101). These researchers held that it was the dust and not the air striking the charged body that was responsible for carrying off the electricity. In this newer view the dust did not even have to be present in the original air. It might, it was believed, be given off by the charged conductors under investigation. Thus Lenard and Wolf demonstrated in 1889 that when ultraviolet light fell on a negatively electrified platinum surface, a steam jet in the neighborhood of the surface showed by its change of color that the vapor had been condensed (63). Lenard and Wolf attributed the condensation of the jet to dust or metallic vapor emitted from the illuminated surface, the dust producing condensation by forming nuclei around which the water droplets coalesced. The experimenters were, of course, observing the photoemission of electrons from the metallic surface by means of a primitive cloud chamber. But being unaware of the existence of electrons or gaseous ions and supposing that dust was indispensable to droplet condensation, Lenard and Wolf were led to conclude that the metal was disintegrating under the action of the light, the metallic vapor carrying off the negative electricity and leaving behind the positive. A similar experiment, directly bearing on the electric wind, was performed by R. von Helmholtz in 1887 (46). He had directed an electric wind against a jet of steam and observed the conversion of the steam to visible fog just as if dust particles had been introduced. The belief that air molecules could not be charged was further supported by the experimental results of Blake in

1883 and Sohneke in 1888 (9, 89). These studies seemed to show that not only is there no electricity produced by the evaporation of an unelectrified liquid, but also that the vapor rising from an electrified liquid does not carry a charge. It was natural enough to argue that if molecules of vapor are capable of receiving a charge under any circumstances they should be expected to do so in this case.

The conviction that the presence of dust is a necessary condition for the gaseous discharge in general and the electric wind in particular died hard. Aspérin reported in 1888 that the presence of dust had no effect on the intensity of the electric wind and therefore could not contribute to its explanation (2).

Lord Kelvin and Magnus MacLean further observed in 1894, "That air can be electrified either positively or negatively is obvious from the fact that an isolated spherule of pure water, electrified either positively or negatively, can be wholly evaporated in the air ... This demonstrates an affirmative answer to the question, can a molecule of gas be charged with electricity? and shows that the experiments referred to as pointing to the opposite conclusion are to be explained otherwise (50)." Despite this F. Braun could write as late as 1896 (11), "The question of whether a gas can be electrified is answered mostly in the negative, at least among German investigators. All phenomena indicating the possibility of electrification can be explained by the presence of dust particles that might have been contained in the gas from the outset or else introduced during the process of electrification." It was not long, however, before the last vestige of doubt on this score was eliminated. X-rays were discovered in 1895. Almost immediately J. J. Thomson at the head of a brilliant group of young scientists at the Cavendish Laboratory of Cambridge undertook to answer the question of how gases are made conductive by the new radiation. It was quickly found that gas rendered conducting this way lost all its conductivity when filtered through glass wool or traversed by an electric field. The conclusion was inevitable that gaseous conductivity was due to the presence of electrified particles. These particles were called ions by analogy with the term coined by Faraday in 1834 with reference to the charge carriers of electrolytic solutions (33, 95).

Quantitative theory of the electric wind. D. Kaempfer, in his inaugural dissertation at Marburg in 1883, seems to have been the first to attempt a quantitative theory of the electric wind (49). Enlarging on the earlier work of Melde (70, 71), Kaempfer derived equations linking the pressure generated by an electric fly with the charge lost in the corona. In 1898, O. Lehman, professor of physics at the University of Halle, published calculations including the velocity of the electric wind as another variable (62). The early theory was based on a number of

questionable assumptions; progress was to be made only by abandoning the old approaches and starting afresh. This was done by A. P. Chattock, professor of physics at the University of Bristol who, in 1899, developed a relationship between electric wind pressure and current for plane parallel electrodes (16). Chattock's pressure-current equation was extended to other geometries by Löb in 1954 (65). In 1957 Harney examined the effects on the electrical parameters of a corona discharge which are brought about by the motion of the gas stream (41). Such effects are small in gases moving at electric wind velocities but need not remain so if a dielectric liquid is substituted for the gaseous medium. Paying special attention to such a case Stuetgen, in 1959 and 1960, further expanded the work of Löb and Harney, giving the most complete analysis of ion-drag phenomena that has yet been offered (90, 91, 92).

Electrical precipitation and the electric wind. In 1930 Ladenberg and Tietze investigated the action of the electric wind in the electrical precipitation process (57). The conclusion of these writers - that the wind plays a significant role in transporting particles to the collecting electrode of the precipitator - was challenged by the experiments of Deutsch in 1931 (30). This, with the results of Mierdel and Sieliger in 1935, provided convincing proof that the cleaning effects obtained in commercial precipitators could be understood without invoking the electric wind (72). In the case of laboratory precipitators, however, Deutsch showed in 1925 that the precipitating force of the electric wind may be considerable (29).

Beadle et al. in 1954 constructed a portable electrical sampling precipitator provided with an electric-wind air flow of 1 m/sec (4). A similar apparatus was patented by Hahn in 1934 (40).

Corona loudspeaker. Much of the recent interest in the electric wind has been relative to the corona loudspeaker. This device consists essentially of a corona-discharge electrode the d-c potential of which is modulated by an alternating signal. The modulated output thereupon appears as pressure variations in the resultant electric-wind. Since there is no ponderable vibrating diaphragm - only gas ions and associated molecules move - higher frequencies than in conventional loudspeakers can, in principle, be achieved.

Tones in 1955 modulated a point discharge by means of a control grid. His loudspeaker had a smooth frequency response to 15 kc/sec and drew no a-c power from an acoustic signal source. Nonlinearity was a severe limitation (93).

A thermionic cell producing positive ions in atmospheric air was devised by Stein in 1946. An emitting surface coated

with a mixture of platinum, aluminum phosphate, graphite and iridium replaced a point electrode (34, 53, 54, 55, 56).

In 1954 Lob made a theoretical study of the relations existing between static electric-wind pressure and applied d-c voltage for plane-parallel, spherical and cylindrical electrode configurations. His equations held within limits also for alternating pressures resulting from a superposition of an a-c voltage on the discharge d-c voltage (65).

Patents. A number of patents have been issued in recent decades on devices for propelling air by the action of the electric wind. Among these may be mentioned the electrostatic blowers of Bennet (7), Slayter (87) and Lindenblad (64). Faluëff proposed to cool high-voltage transformers by surrounding them with corona discharge points (78). Hahn devised a combination blower-electrical precipitator in which the corona simultaneously charged suspended dust and generated the pressure needed to insure gas flow through the system (40).

Miscellaneous work. At the turn of the century, one of the first problems connected with the then newly discovered mechanism of gaseous conduction was that of measuring ionic mobility, the velocity of an ion in unit electric field. Chattock succeeded in determining ionic mobility in 1899 by establishing a relationship between the mobility and the pressure of the electric wind (16). Chattock's later work in 1901 and 1910 extended these measurements to other gases than air (17, 18). A variant of this technique was developed by Ratner in 1916 (82). The electric-wind method for measuring mobilities is relatively inaccurate and has today been completely replaced by more satisfactory modern procedures.

The first quantitative study on the electric wind appears to have been performed by Holtz. In 1880 he determined the velocity of the electric wind both by observing the rotation of an electric fly and by measuring the pressure produced by the wind against an adjacent surface (47).

Von Obermeyer and von Pichler measured the velocity more directly, in 1866, by means of an anemometer (76). They investigated the electric wind from a bundle of discharge points as well as from a single point. By hooking three influence machines in series they attained voltages of up to 65 kv.

Lehman, in two publications, in 1897 and 1898, gave an extensive qualitative account of the electric wind. The electric wind was used to explain certain stratified electrical discharges and the shape and behavior of the electric arc. The wind pattern as a function of the electrode geometry was considered and the phenomenon of the 'magnetic wind' was introduced.

The latter is the name Lehman gave to an electric wind deflected in a magnetic field, an effect which in gas under room conditions, is insignificant (61, 62).

The distribution of the electric wind velocity in terms of electrode geometry, current and voltage was considered by Heiser in 1955 (44, 45).

Auer and Sharbaugh reported on the pumping of dielectric liquids by a corona discharge in 1958 (3). A method for producing low-current high-voltage power by transporting electrical charge in a moving gas stream, instead of a belt as in a van de Graaf generator, was described by Gourdine in 1960 (37, 38).

Other recent writers to mention the electric wind include Warburg in 1927 (104), Thomson in 1933 (94) and Von Engel and Steinbeck in 1934 (32).*

* Work of related interest dealing with the movement of liquids in electric fields includes Vonnegut, B. and Neubauer, R. L., "Production of Monodisperse Liquid Particles by Electrical Atomization," J. Colloid Sci. 7, 616-22 (1952); Drozin, V. G., "The Electrical Dispersion of Liquids as Aerosols," J. Colloid Sci. 16, 158-64 (1955); Nawab, M. A. and Mason, S. G., "The Preparation of Uniform Emulsions by Electrical Dispersion," J. Colloid Sci. 13, 179-87 (1958); Pohl, H. A., "Some Effects of Non-uniform Fields in Dielectrics," J. Appl. Phys. 29, 1182-8 (1958).

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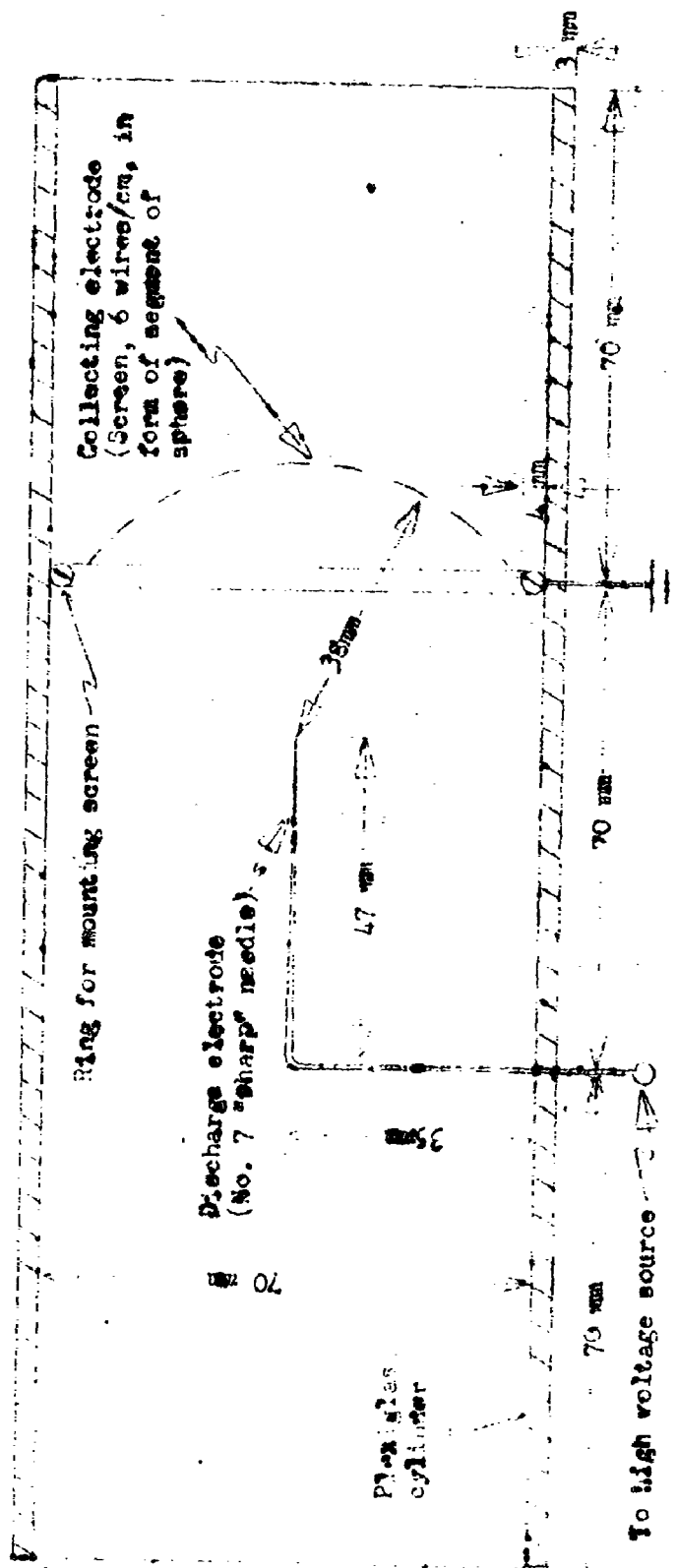
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FIGURE 1. Needle-screen over (1:1 scale)

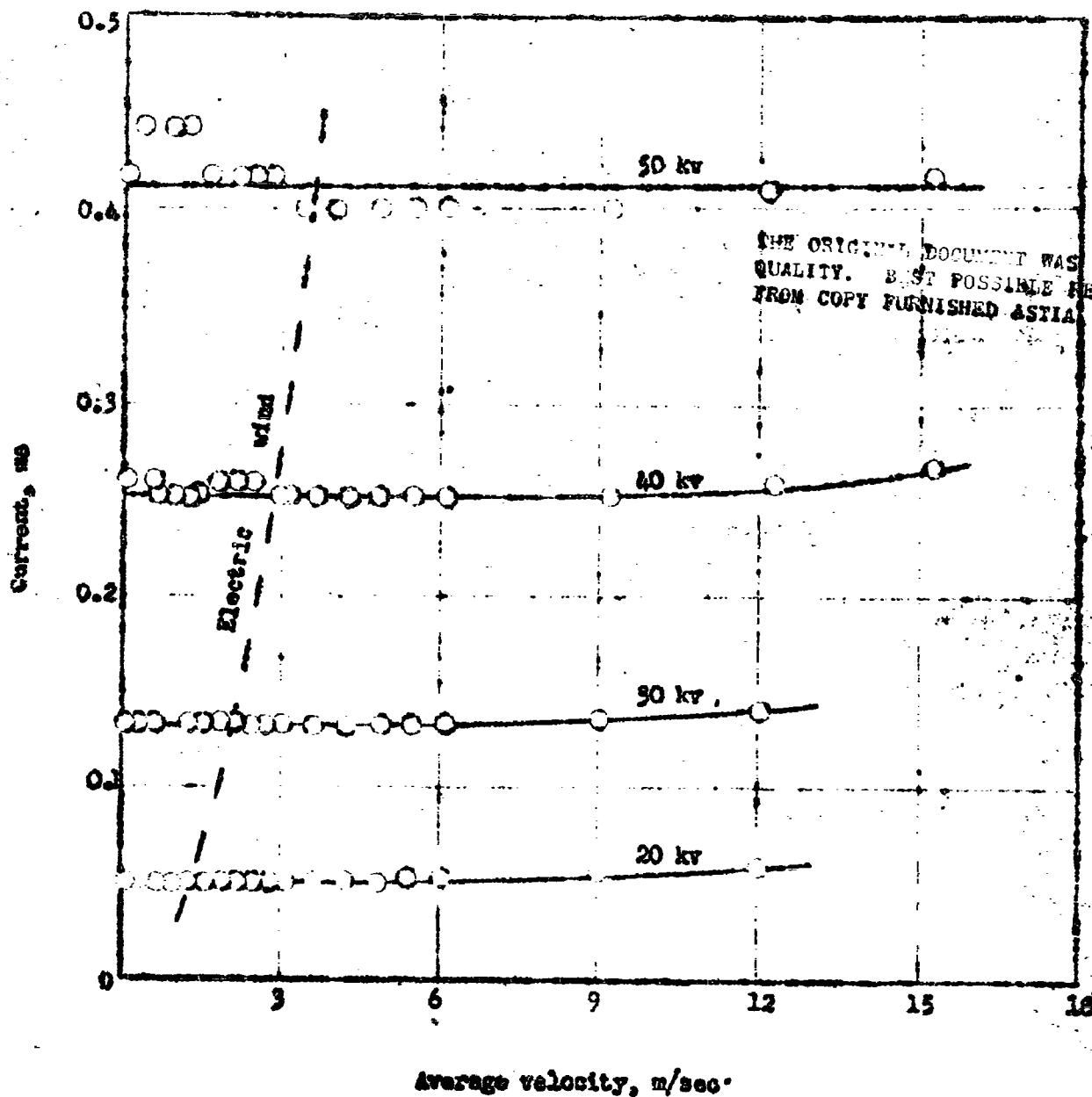


FIGURE 2. Effect of air velocity on the corona current. Corresponding velocity-current values for the electric wind in the needle-screen flow are shown by the dashed curves (Equation (1)).

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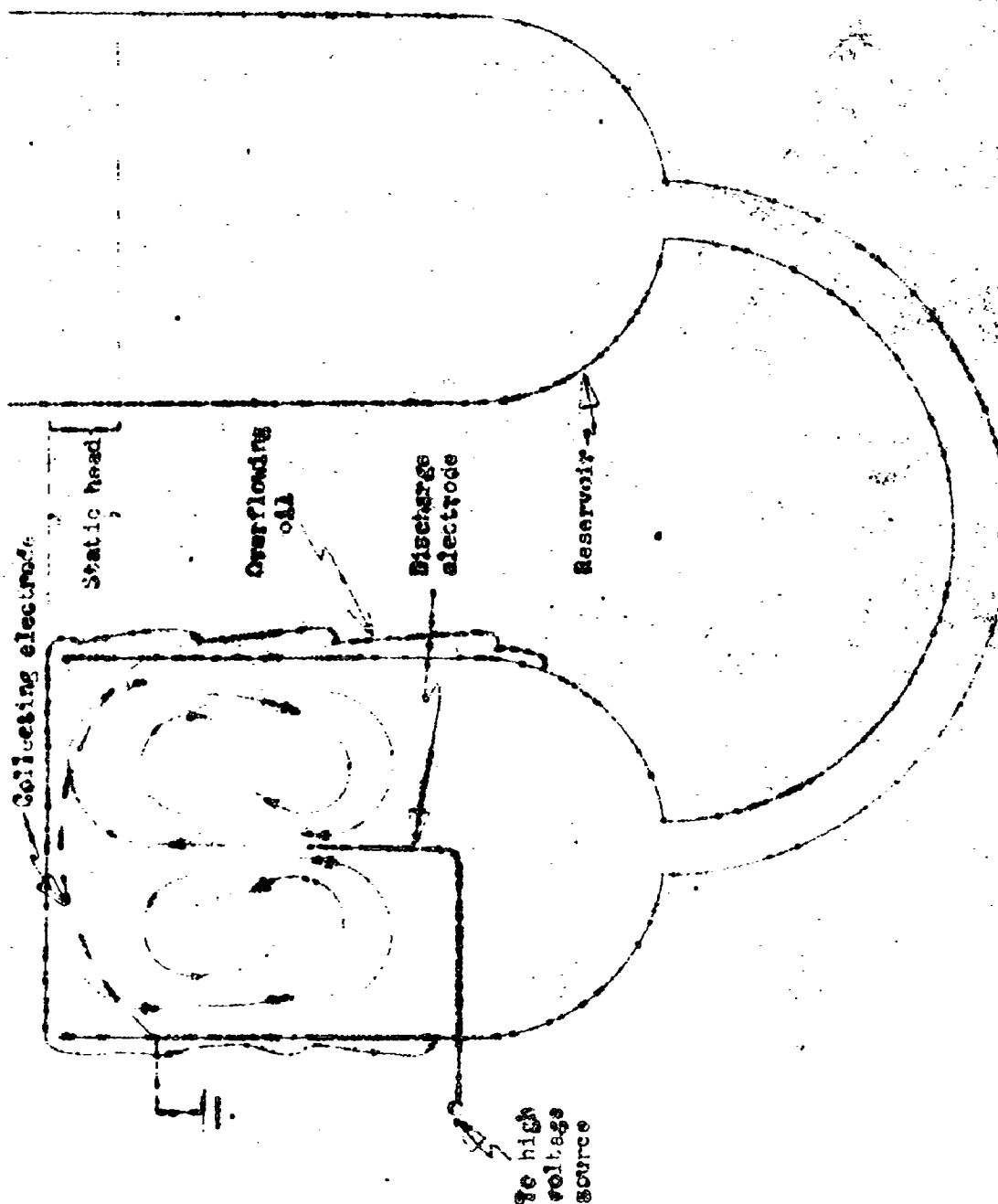
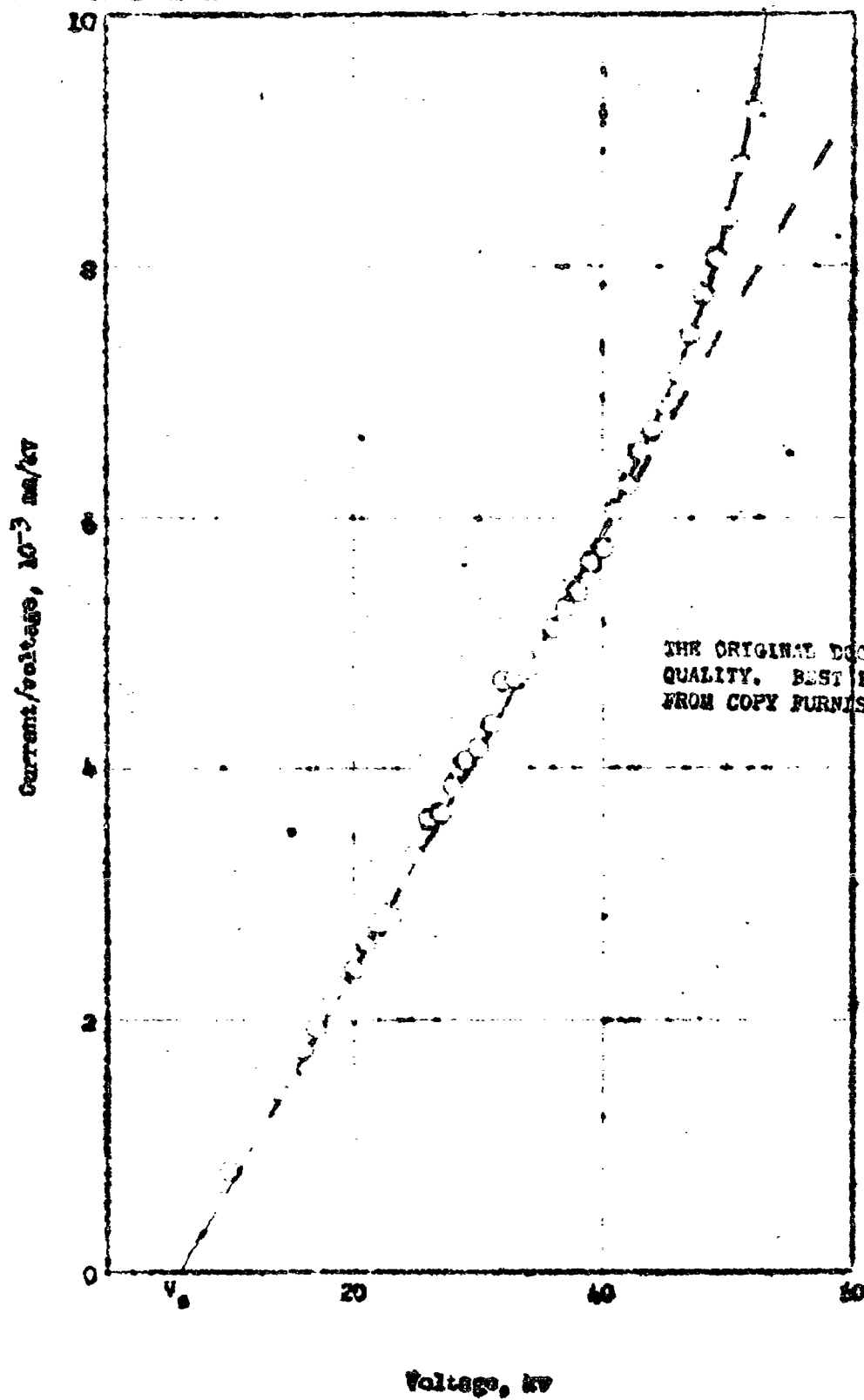


FIGURE 3. Liquid "blower" demonstrating internal circulation



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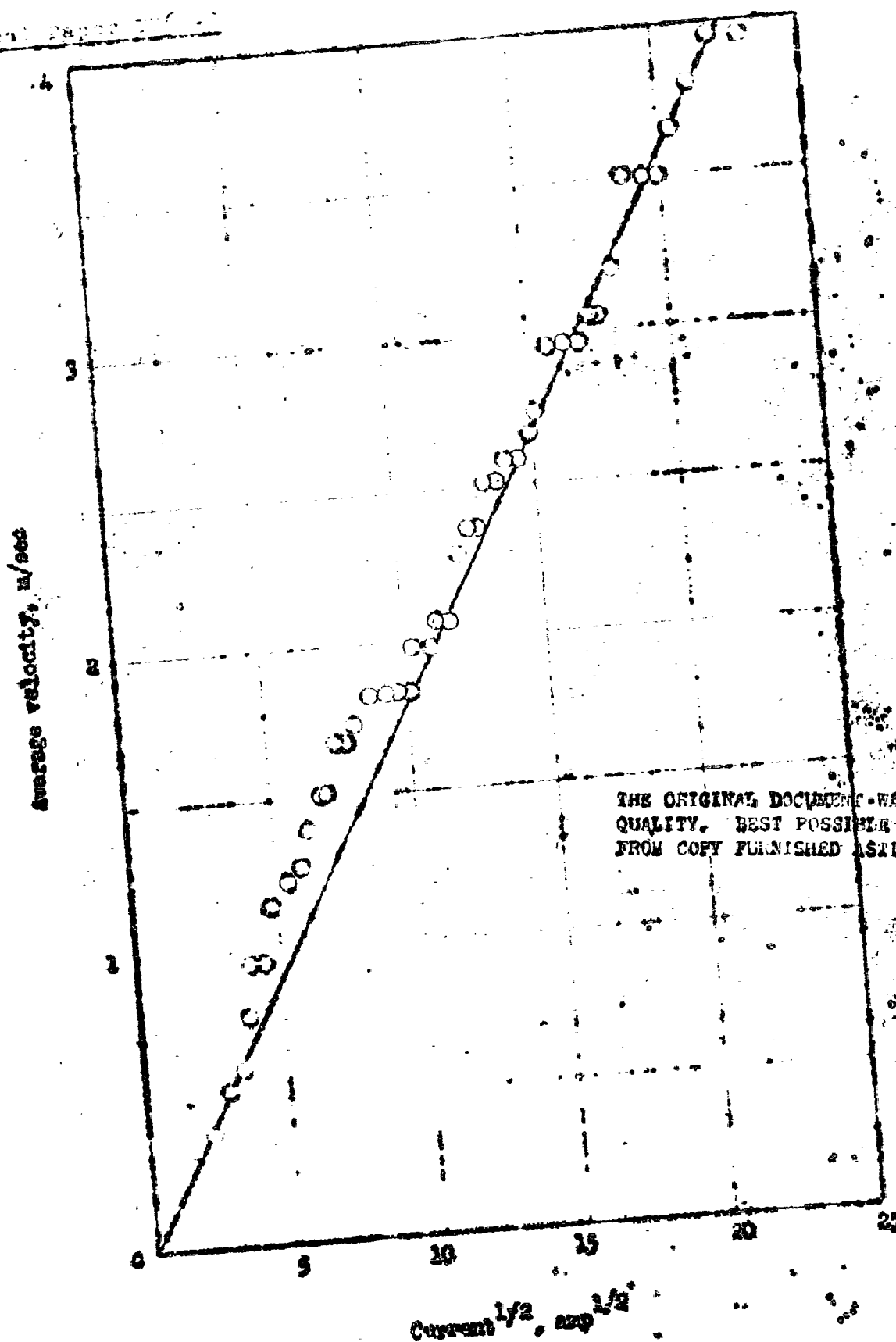
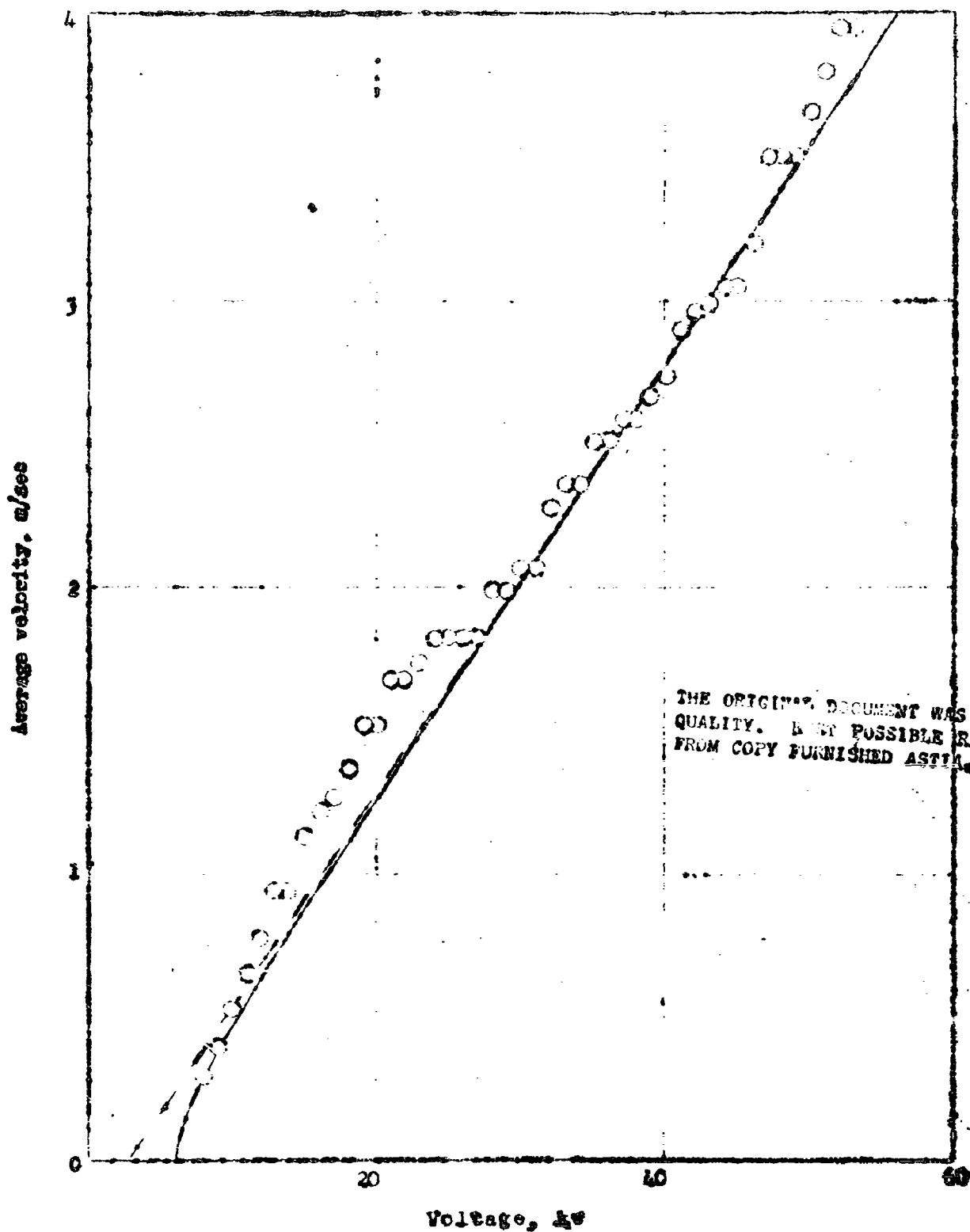


FIGURE 12. Characteristic velocity-current relation. The line is that of equation (14)



The "c-curve" is a function of voltage. The solid curve shown is to Equation (17), the broken line to Equation (12).

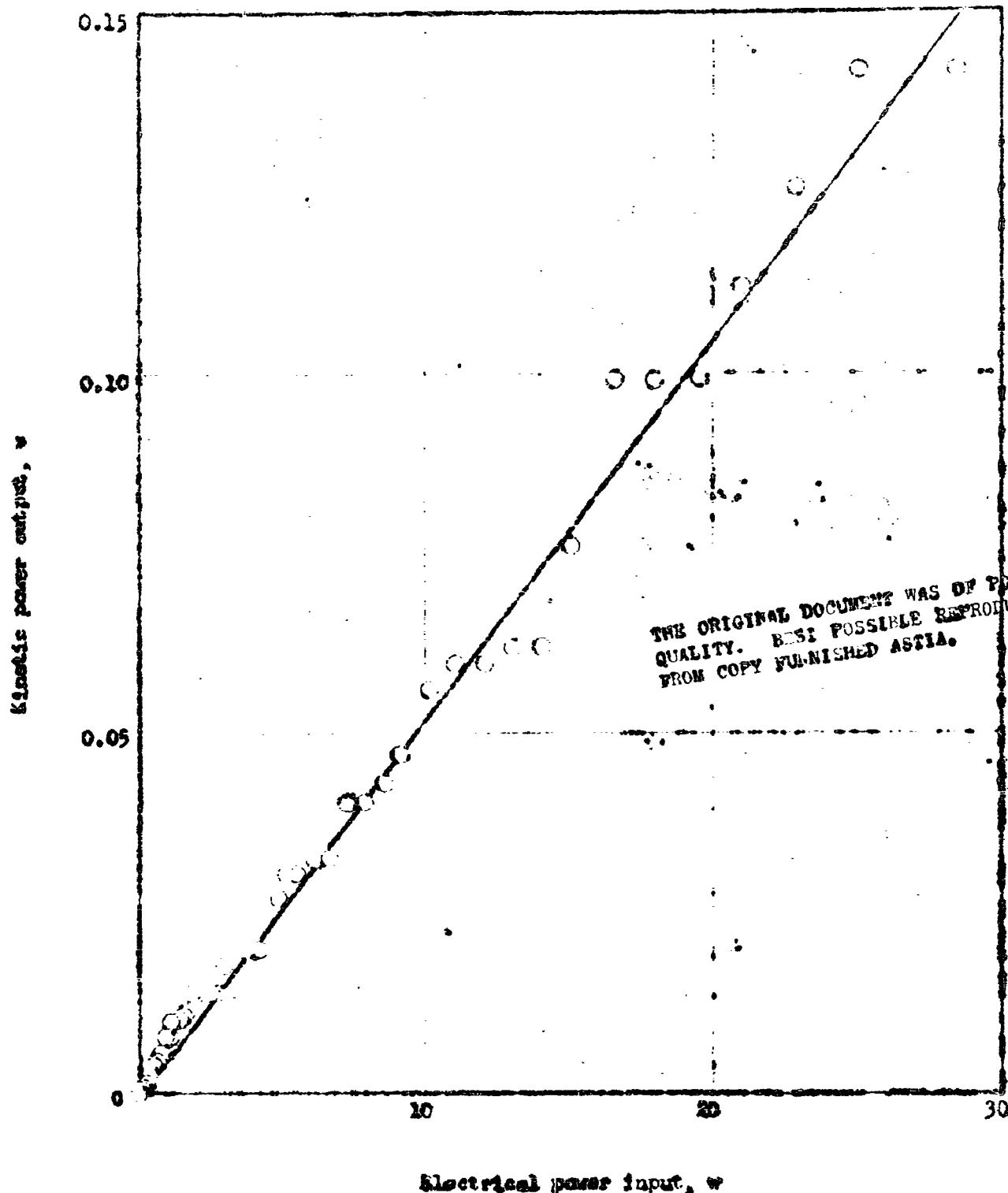


FIG. 1. Kinetic power output vs. electrical power input. The curve shows the best possible reproduction from the original document.

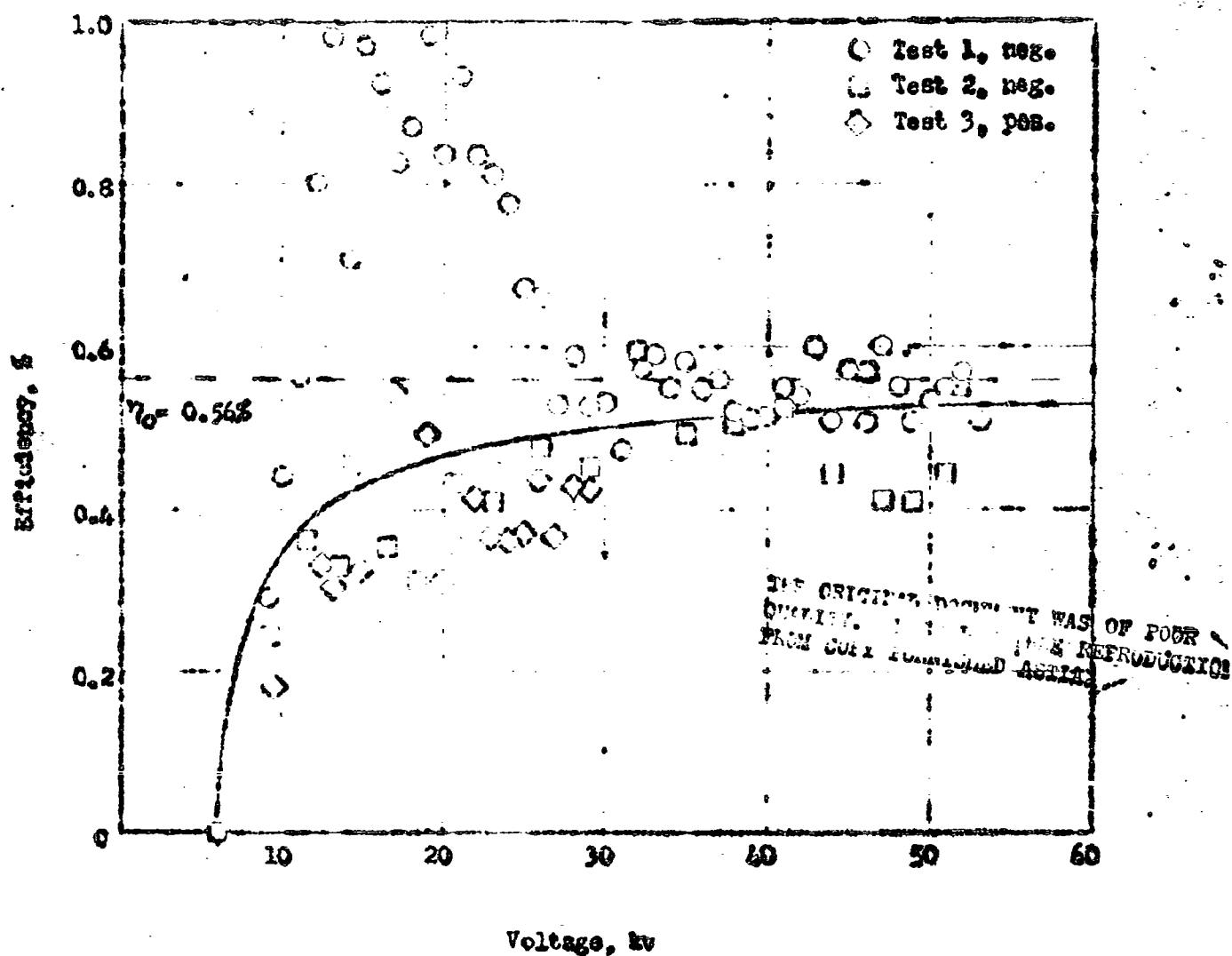
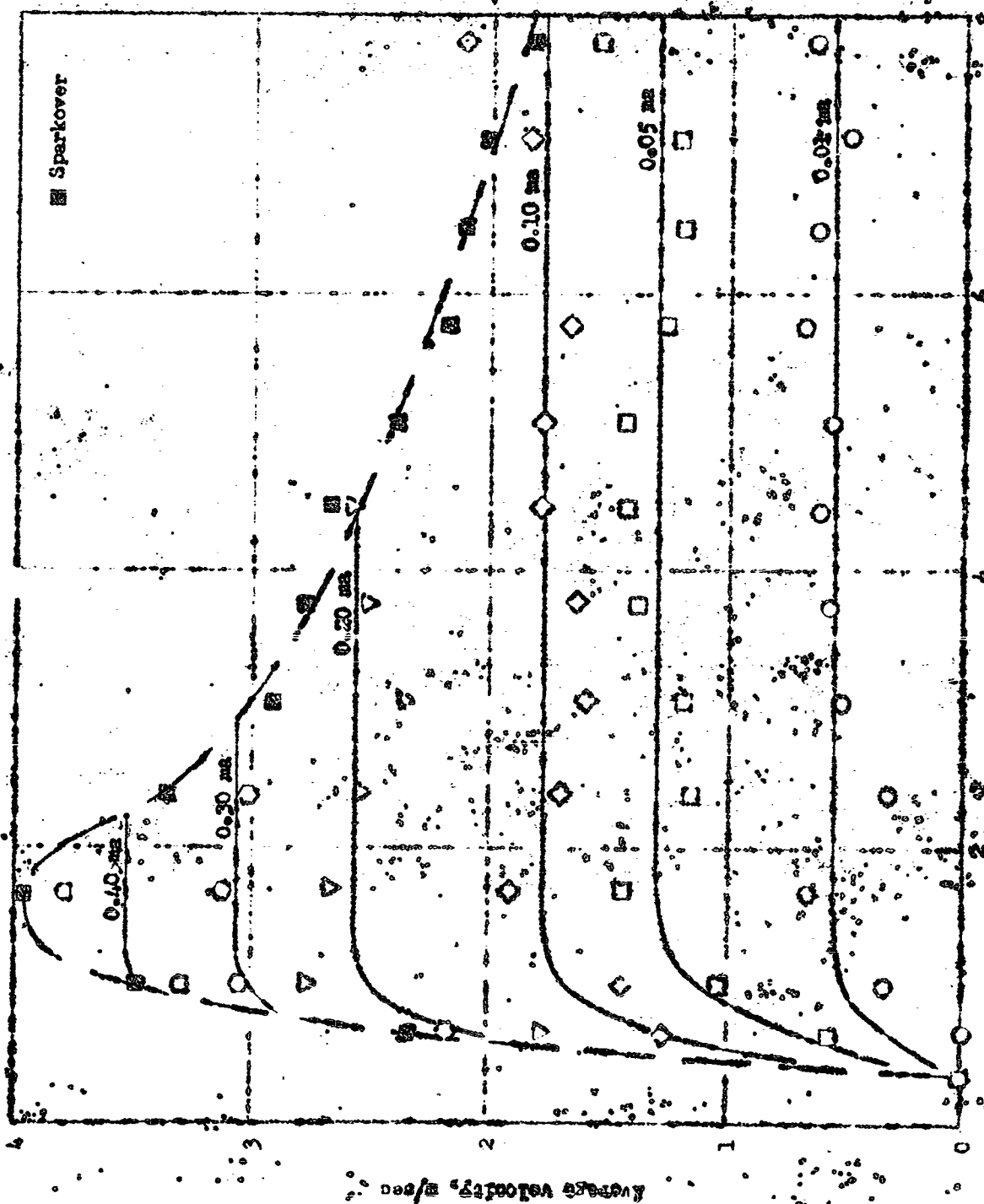


FIGURE 9. Example of the variation of efficiency with voltage. The curve is that of Equation (2).

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Relative gas density, ρ_g/ρ_o

Figure 9. Electric-wind velocity as a function of air density and corona current. The straight-line portions of the curves closely agree with equation (14).

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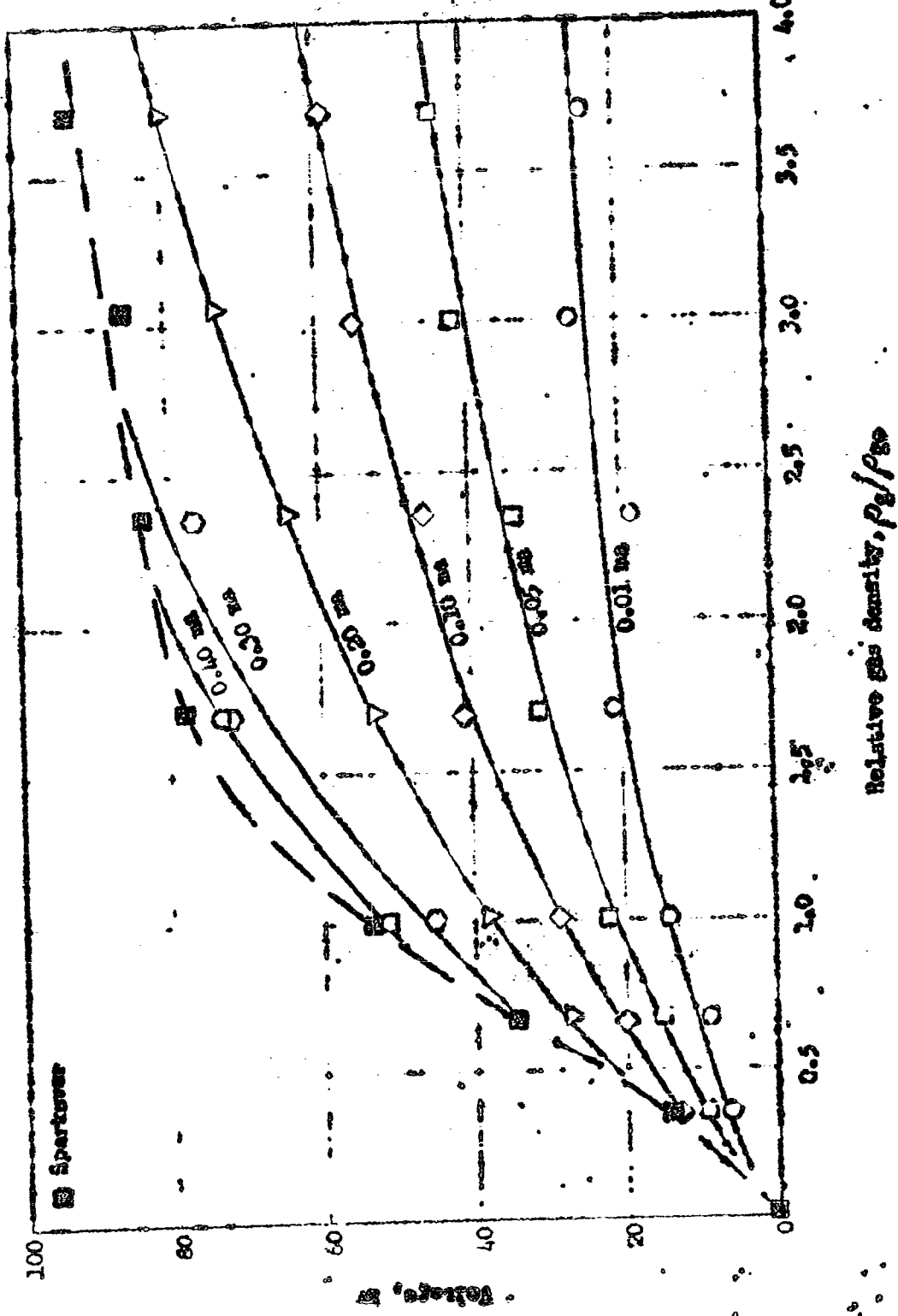
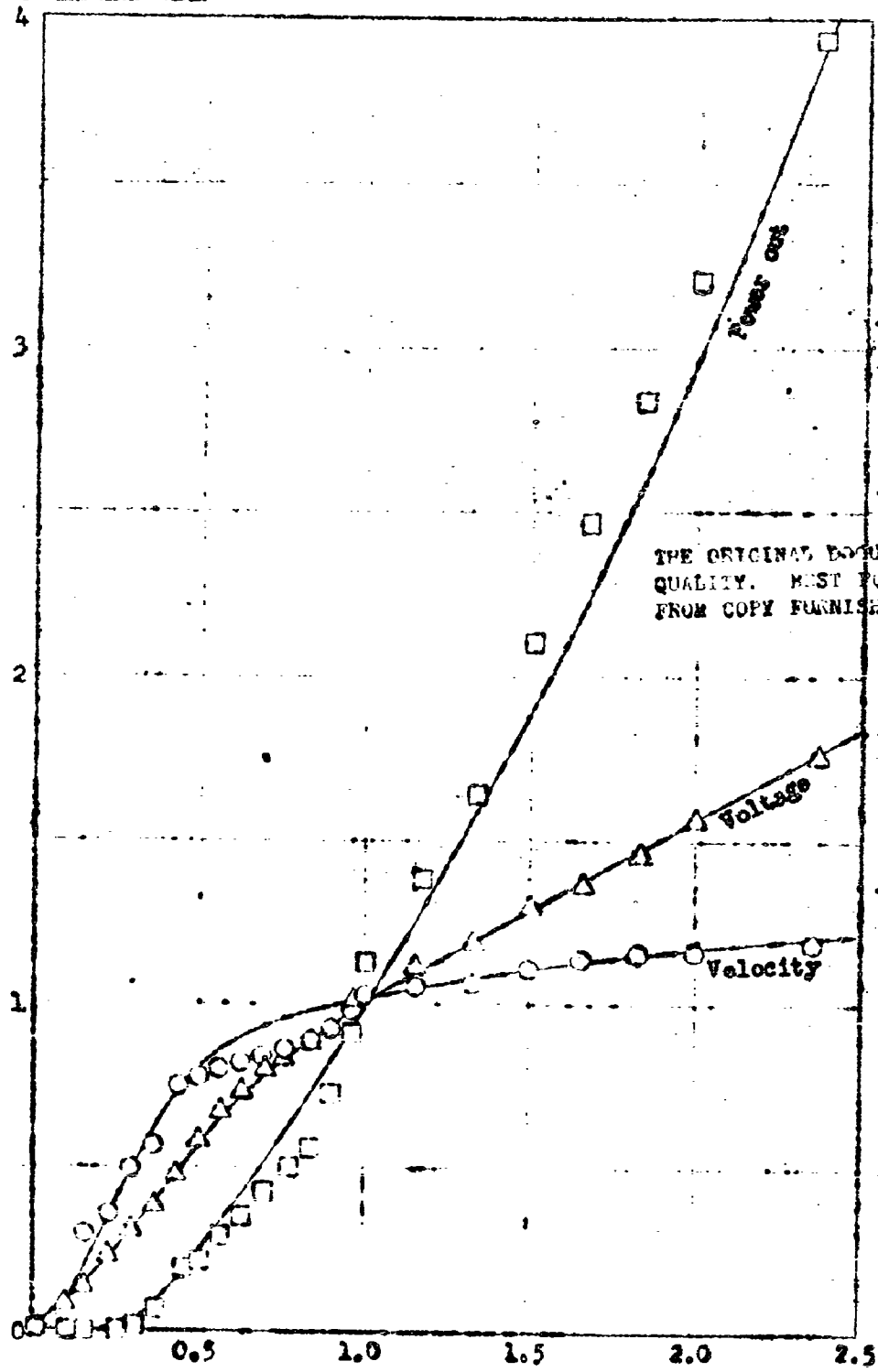


FIGURE 1. Dependence of voltage on air density. Upper and lower sparkover voltages are shown for various currents.

Relative power output, voltage and average velocity



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Relative gas density, ρ_g/ρ_{go}

Fig. 2. Power output, voltage and velocity as a function of relative gas density. The data are relative to the conditions of operation. Power and voltage are calculated from Equation (10) and (11) respectively.

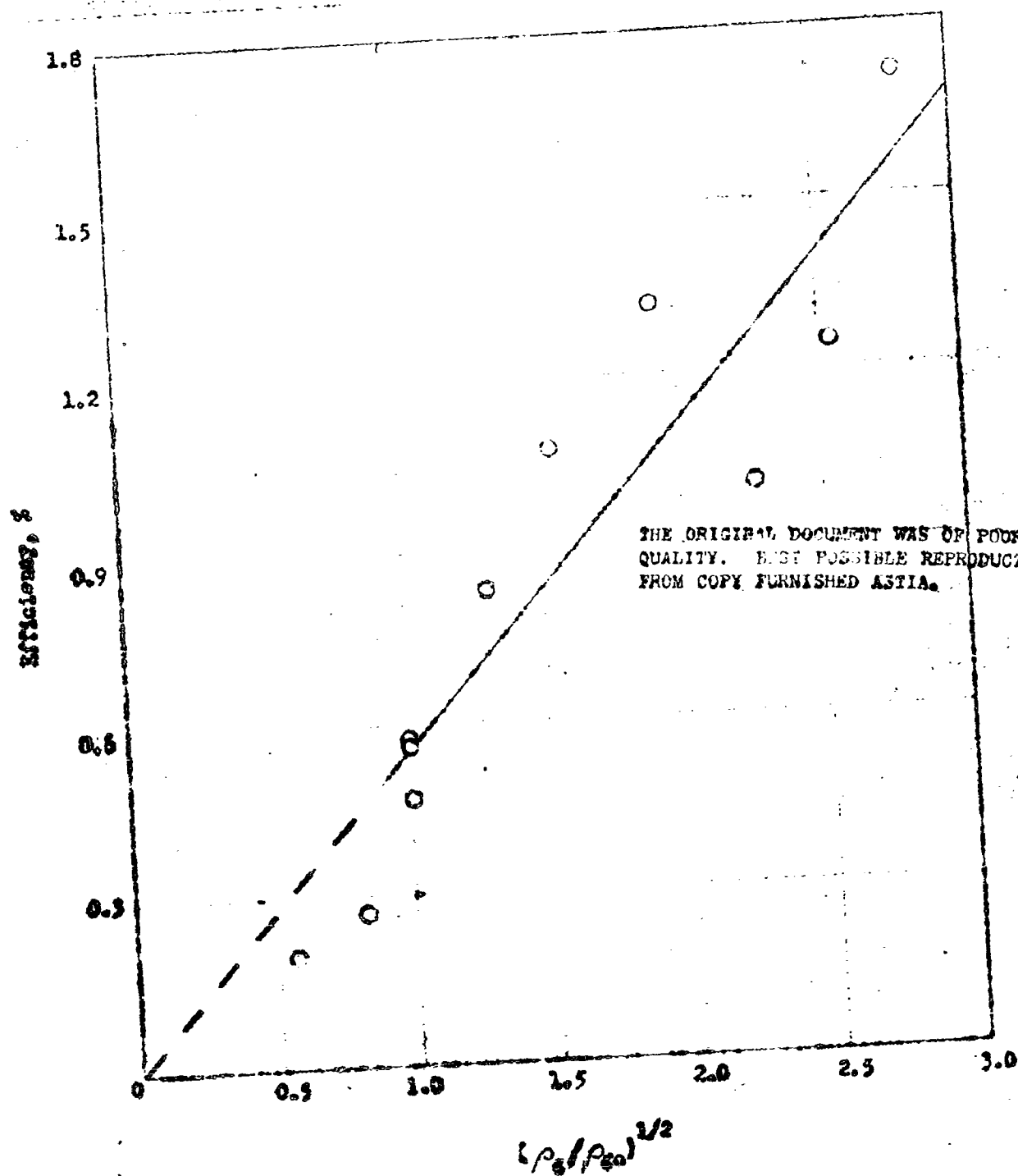
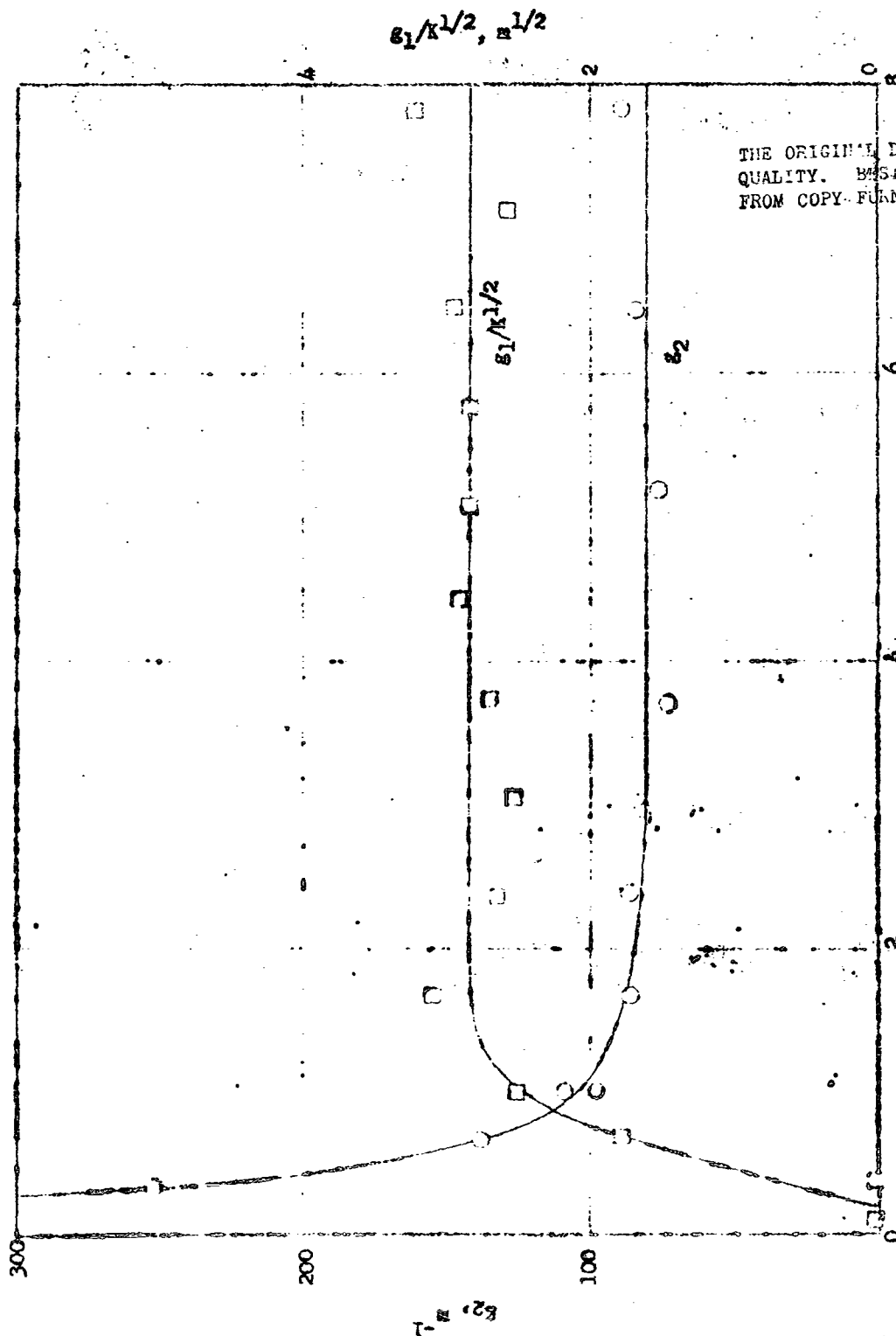


FIGURE 1. Efficiency of air filter relative air velocity.
 (Data from Figure 1 of Reference 13).



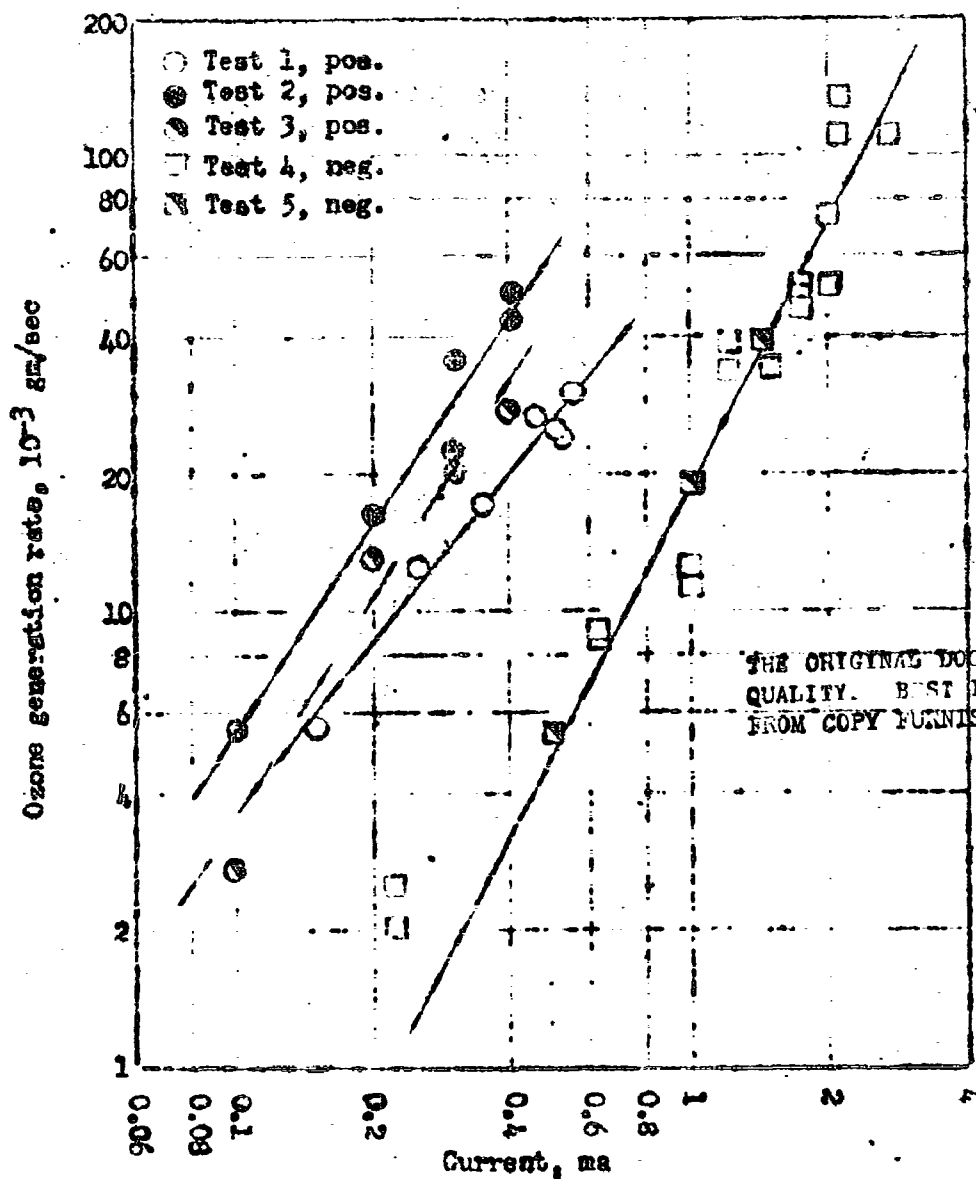


FIGURE 10. Example of ozone-generation rate in terms of corona current. Data are for five bladders in series.

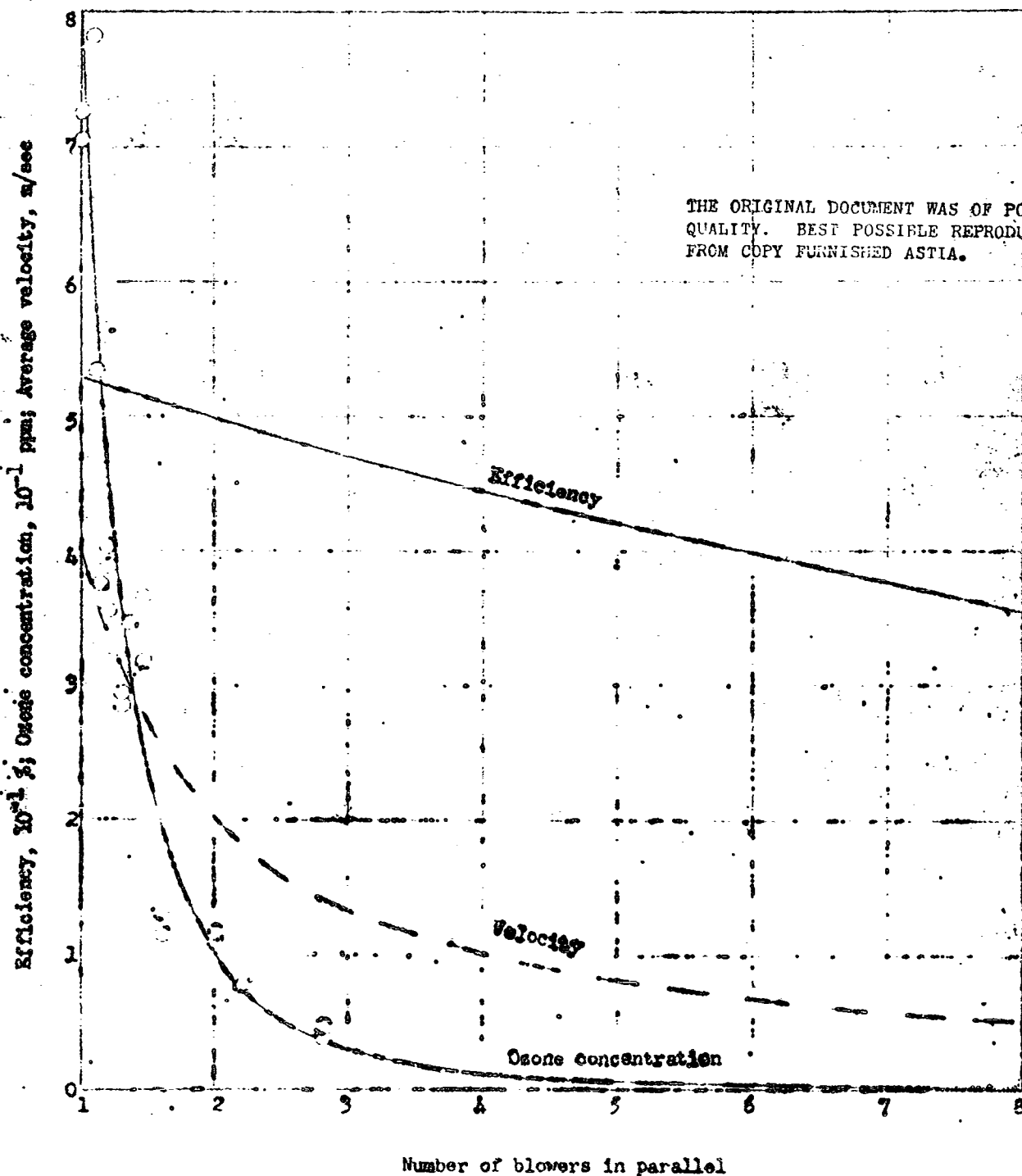


FIGURE 1. Efficiency, ozone concentration by volume, and velocity resulting from running diffuser at numbers of blowers in parallel at constant total volumetric flow rate. The efficiency curve is taken from Equation (10), and the ozone curve from Equation (10).

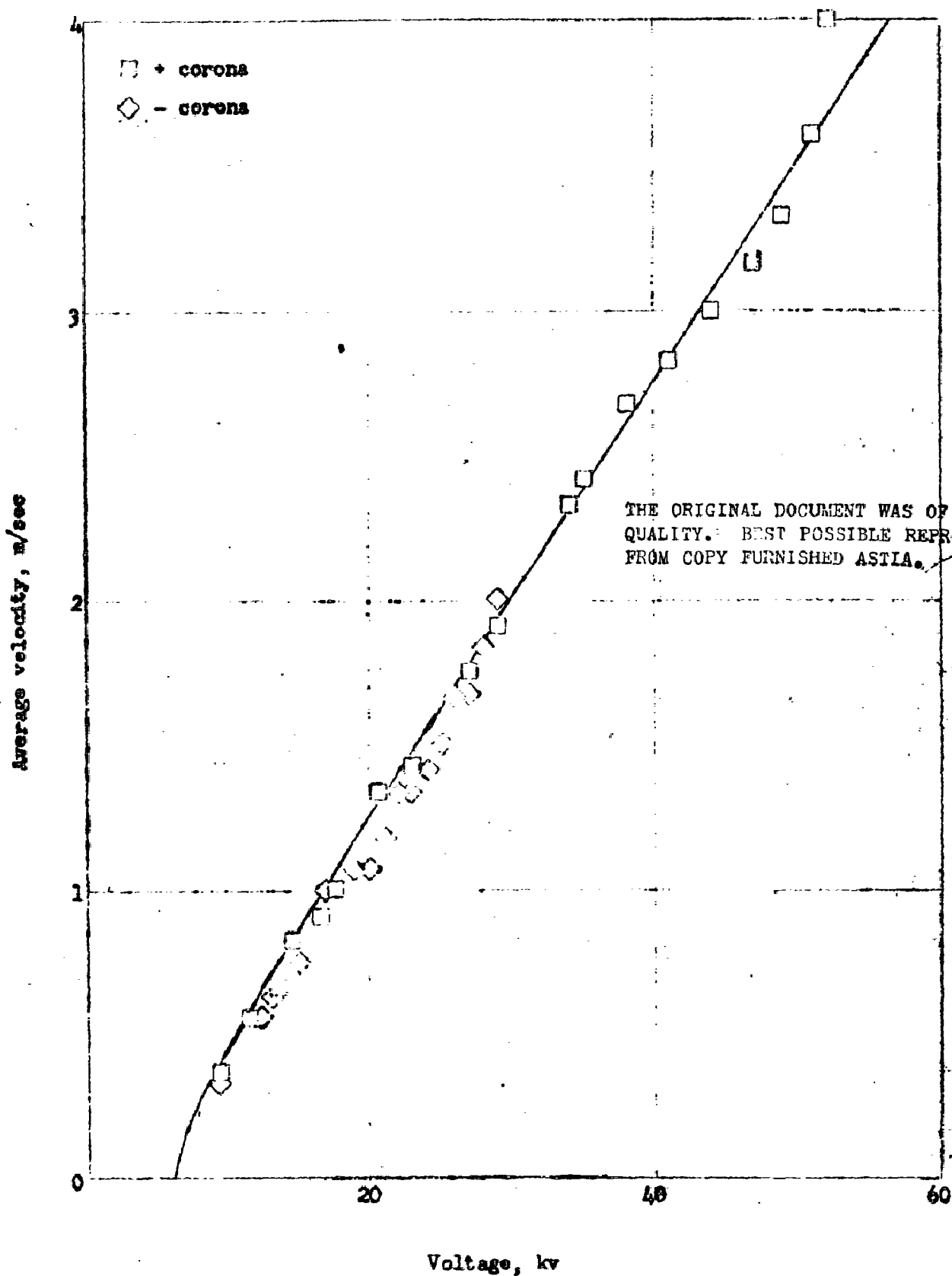


FIGURE 17. Comparison of positive and negative electric-
 al velocity as function of voltage. The curve is
 that of equation (17).

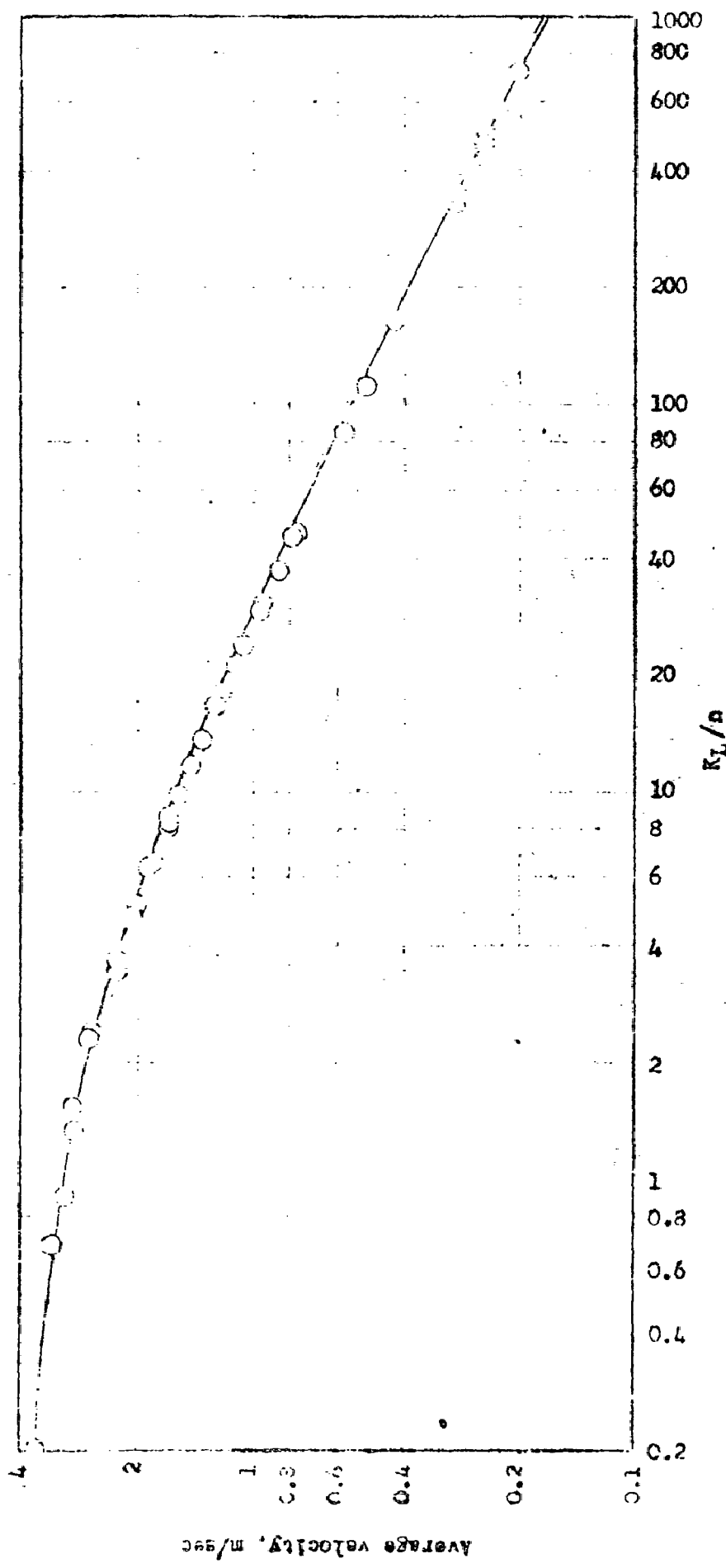


FIGURE 16. The effect of external load on air velocity. The curve follows Equation (55).

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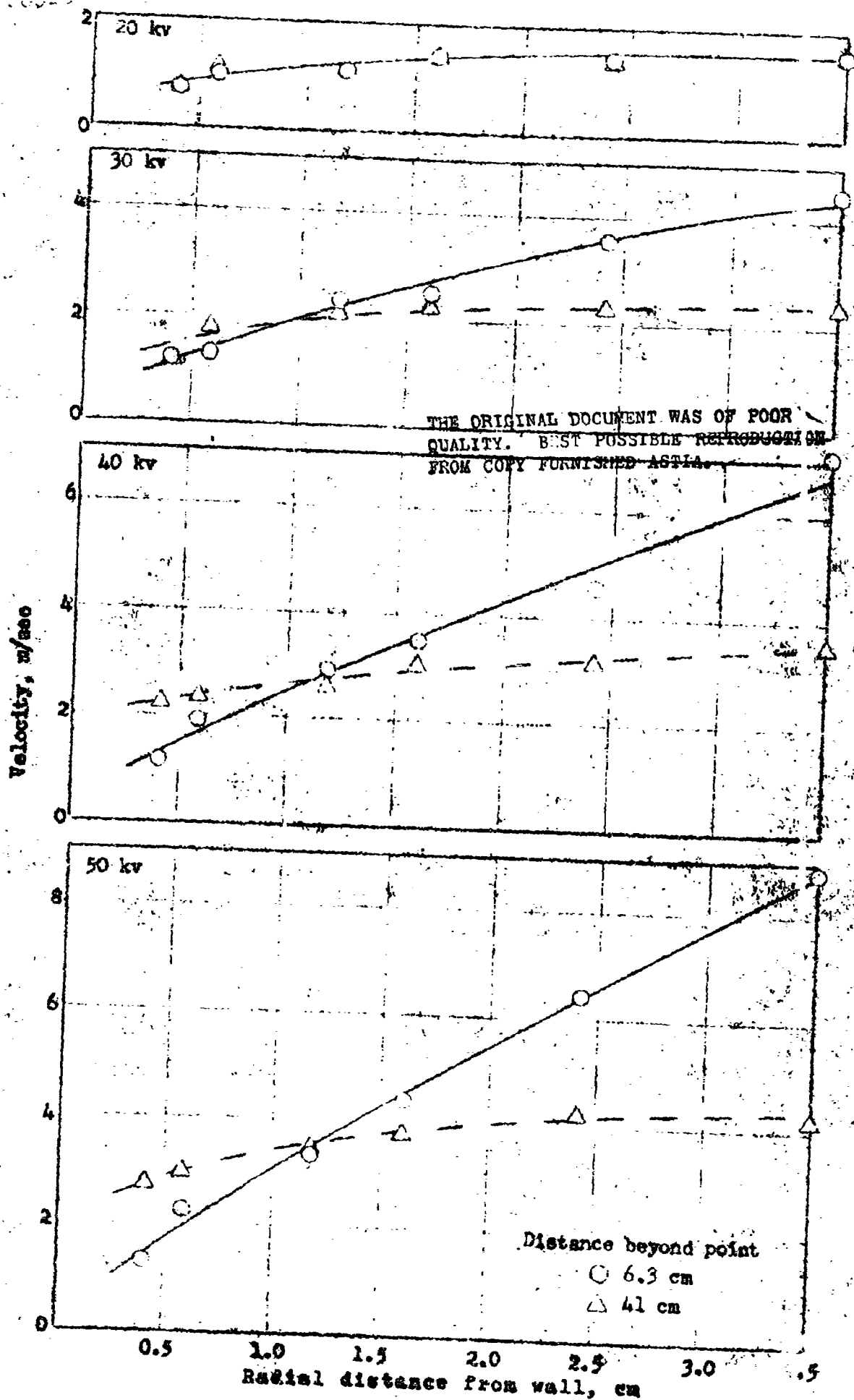


FIGURE 19. Velocity profiles as a function of downstream distance and applied voltage.

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